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Risk vs. Reward: A Methodology to Assess Investment in Marine Energy

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Abstract: The majority of WEC (wave energy converter) projects are expensive and pose a large risk to a developer. Currently no developers have been successful in commercialising a WEC. So far, many wave energy feasibility studies have only considered the LCOE (levelised cost of electricity), assessing investment in marine energy technologies from a purely financial point of view. No previous studies have, however, explicitly accounted for development risk as well as the LCOE to determine the feasibility of a project. This paper proposes a new methodology that can be used to account for both risk and the LCOE to give a clearer picture of the feasibility of a WEC development. By combining the LCOE and risk score for a particular development, the "value for risk" can be calculated, presented here as the "RR ratio" ("Risk/Reward ratio"). A number of case studies were chosen to test the model, investigating the RR ratio for a number of different WEC technologies and ranking them to suggest an optimal development path for the industry. Results showed that projects that combine many innovative technologies provide the best "value for risk". These devices overall had the highest risk, suggesting that multiple developers are likely required to collaborate in order to reduce the risk down to acceptable levels for each.

Keywords: marine energy; risk; reward; LCOE; investment

1. Introduction

The marine energy sector is a newly emerging industry, still in its early stages of development, but with significant potential to contribute to the UK energy mix [1]. Promising marine energy technologies are considered to consist of tidal stream and wave energy converters; however, this study specifically focusses on wave energy. The current problem facing the wave energy industry is that it is expensive compared to its main competitor, offshore wind [2]. Offshore wind is predicted to fall to costs of 0.1 £/kWh by 2020 [3] and it is important that marine energy also reaches these levels within a competitive time frame to ensure it is competitive with offshore wind. Producing electricity from ocean waves has proven to be very difficult, with the main technical challenges being survivability and energy capture from the waves [4]. A number of WEC concepts have been tested by different developers within the industry; however, none have managed to produce a commercially viable solution and most projects have failed, with prototypes not surviving the harsh marine environment, leading developers to bankruptcy. Innovation theory suggests that the industry is in need of a dominant design to emerge before economies of scale can be successfully utilised to drive cost reductions [5]. Until this happens, marine energy will not be commercially competitive. This paper aims to provide a methodology that can be used by developers in order to de-risk the development approach and identify the optimal development path for their device.

Traditionally, investment in marine energy has been assessed in terms of LCOE, or levelised cost of electricity. The LCOE calculation is well established and its use is standard practice within the energy generation sector. The IEA (international energy agency) periodically publish a report that outlines the LCOE calculation of all different forms of energy production, including marine renewables [6]. Many techno-economic analyses have been carried out to assess the feasibility of marine energy. O'Connor et al. conducted a study to investigate the effect of differing wave energy resources at different geographical locations and the impact this has on LCOE [7]. De Andrés et al. [8] conducted a study investigating the effect of differing development strategies on LCOE. Furthermore, consulting engineer Julia Fernandez Chozas has developed a tool to standardise the process for calculating the LCOE of wave energy developments, allowing input variables to be changed in order to investigate the effect of design changes on the final LCOE [9]. While these examples show that large amounts of work have been done to investigate the effect of device and deployment parameters on the LCOE, the studies do not directly address the risks posed to a developer when investigating differing development paths. This paper adds to the existing literature by analysing both the LCOE and the development risk, thus filling this gap in the literature.

By their very nature, WEC projects are highly complex in terms of their organisational requirements to be successfully implemented and in terms of pushing the boundaries of our understanding of marine engineering. Due to the complexity of these projects, a developer is exposed to many hazards throughout the development process, which may delay or detriment the project.

Risk is defined as the chance of a hazard occurring [10]. Devices are deployed in very hostile marine environments, posing a hazard to developers that the device might be damaged or destroyed by the sea. Furthermore, WECs must be commercially competitive with offshore wind, a technology that is considerably further developed. This presents a hazard to a developer that if wave energy is not commercially competitive with offshore wind, the industry will never commercialise. Managing risk is of great importance to project owners, especially on large projects where significant capital expenditure is tied up, and the consequences of failure are severe. Such is the case with wave energy.

OPERA is a EU-funded project which aims to collect and share open sea operating data and experiences in order to de-risk marine energy technologies and lead to significant cost reductions. OPERA deliverable D7.1 "Initial risk and failure data collection protocol for H2020-OPERA project" identifies risks within wave energy, and highlights that the project risk of WEC deployments increases when more innovative technologies are implemented [11]. The results of this study show that effective risk management is crucial to driving down the cost of marine energy. Despite this, few studies were found to explicitly assess the risk as well as the LCOE of different design changes and product development paths.

A study by Weber details how the TRL (technology readiness level) and TPL (technology performance level of a device can be used to identify a promising technology for development; however, this was deemed to only account for development risk in a minor way, falling within the TRL of a technology [12]. Farrell et al. were found to account for risk in an LCOE analysis by considering the probability of a return on the investment for different-sized wave farms through calculation of the Value at Risk (VaR) and Conditional Value at Risk (CVaR) [13]. This method accounts for risk in a probabilistic way, using the uncertainty of data within the LCOE calculation. This information is useful to a developer in the later stages of developing a WEC technology, when financial data for the LCOE analysis is more certain, allowing them to fine-tune their development approach to yield the highest rate of return. It was, however, determined that this method would not be suitable for analysing technologies in the early stages of a WEC development, due to the vast uncertainties in LCOE input data. It was therefore decided that a more qualitative risk analysis is required, which is the gap that this paper is intending to fill.

It is important that the development risks are assessed in tandem with the LCOE to ensure that unfeasible development strategies can be identified at an early stage and discarded, no matter how attractive the LCOE of the proposed development may seem from a purely financial point of view. By managing the wave energy development risk in this way, we increase the likelihood that marine energy developers will be successful in their efforts to identify promising technologies and allow a dominant design to emerge.

Moody et al. has highlighted that project development risk is dependent on two simple categories: the "design difficulty", and the "resources" required, which are introduced in Section 1 [14]. These categories are scored based on a number of metrics that indicate the extent of the "design difficulty" and "resources" required for the particular project. "Design difficulty" reflects the risks presented by the technical complexity of the design, and "resources" represents the risks presented by the physical resources required to complete the project. These categories can be plotted against each other to graphically display their relationship for a given project. When the risks for many projects are displayed on the same plot, the risks for each can be compared and categorised. This allows for the easy identification of projects that pose smaller risk to a developer. Literature has devised four quadrants in which projects can be placed according to their risk score; these quadrants are shown in Figure 1.

- "Consumer products" is the largest category and encompasses most projects. These projects are of a low to moderate design difficulty, requiring a low to moderate number of resources. This is representative of the majority of projects, which are considered an acceptable risk to a developer.
- "Star Wars" represents projects that are possible within our imagination, but technically not feasible using today's technology.
- "Seven wonders of the ancient world" represents projects that require a vast amount of resources, however, are small to moderate in terms of design complexity.
- "Moon landing" represents projects that are both technically very challenging, pushing the boundaries of technology, and requiring a vast amount of resources to complete, such as the moon landings of the 1960s and 1970s.

The position of each project relative to the others can be used to determine in which quadrant it lies, which can be used to categorise the project's risk. Put into a wave energy context, this shows that development risk should be classified by "design difficulty" and "resources" to show the impact of various design changes on each. Some changes will affect the design difficulty risk, and others will affect the resources risk, ultimately affecting the organisational requirements of the project, and how the design change is classified relative to other alternatives. By categorising a number of projects in this way, the feasibility of each can be compared.

Moody et al. divides these two risks into a number of metrics that can be used to evaluate the risks posed by each. The literature shows that different projects exhibit differing levels of risk related to each of these metrics, showing that as a design changes, so does the allocation of risk. It was recommended that specific metrics should be developed for each category that are tailored to the specific application. It also highlighted that a consistent set of metrics must be used in order for a meaningful comparison of results.

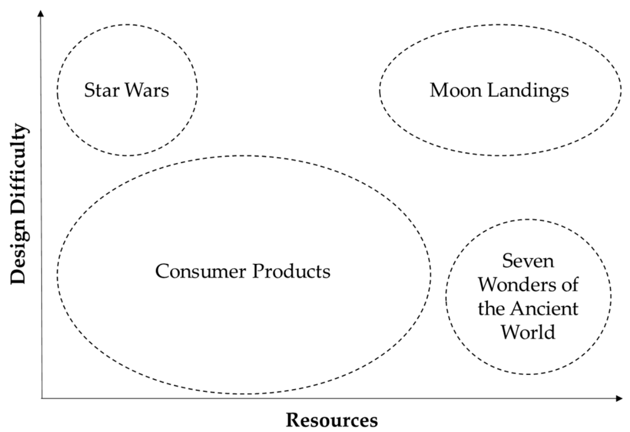

Figure 1. When a project's design difficulty and resources risk is plotted on the same set of axes, the total project risk can be categorised and used to indicate the organisational requirements of the project [14].

Analysis of recent marine energy developments suggests that some developers have opted to develop devices that use existing, well-established and low-risk technologies in a novel way to convert the motion of the waves into electricity [15]. This has the advantages that the knowledge and components to make the device are readily available, thereby reducing the design difficulty risk. However, as the technologies used are already well established, there is limited scope for cost reduction through learning by doing, and the main driver of cost reduction is achieved through economies of scale. This has caused many developers to make their first devices relatively large scale to reduce the LCOE to an acceptable level. This strategy introduces significant development risk in terms of the resources required to implement the technology, however, less risk in terms of design difficulty. The proposed methodology allows the trade-off between design difficulty risk and resource risk to be compared against the LCOE, to determine which kinds of projects developers should pursue to reach the lowest cost of electricity.

The proposed method evaluates both the LCOE and the perceived project risk a developer faces when pursuing different projects. The ratio of the LCOE and development risk is proposed as the "RR ratio". The RR ratio is an indication of the "value for risk" of a development. When the RR ratios for different projects are compared, we can identify the projects which offer the most efficient utilisation of development risk to drive down the cost of electricity. By considering the ratio of the LCOE to the development risk, the "value for risk" of different development approaches can be compared. By pursuing development approaches in order of the best value for risk, technologies that have the largest impact on the final LCOE can be prioritised, in order to highlight an optimal development path for the wave energy industry. The significance of this work is such that it allows different development approaches for marine energy, which is in urgent need of convergence on a dominant design, to be assessed in order to evaluate the best "value for risk" development strategies.

The methodology proposed in this paper provides a framework for assessing the value for risk of the development of a WEC, allowing developers to identify the optimal development path for their device. The methodology is demonstrated using a number of case studies, which model the LCOE and development risk of different design changes for two different WEC devices. Results are compared and ranked, showing how the model can be used to identify the optimal development path for WEC technologies. Section 2 describes the proposed methodology used to analyse the case studies. Section 3 presents the results obtained from the analysis in terms of the risk, LCOE and RR ratio, and discusses the significance of these results and demonstrates how this method can be used to identify the optimal development path for marine energy. Finally, Section 4 concludes the main findings of this paper.

2. Methodology

2.1. Methodology Overview

The proposed methodology works as follows: first a WEC development is selected for analysis. The LCOE of the development is then calculated with the methodology detailed in Section 2.2, where the calculation method is summarised and a detailed account of the input data used for the analysis is given. The development risk of the project is then assessed using the methodology proposed in Section 2.3, where the identified development risks are presented along with a scoring matrix for each. Once the LCOE and risk are calculated, the values are combined to form a novel value which is referred to here as the "RR ratio", which gives an indication of the value for risk of the development. The RR ratio calculation is detailed in Section 2.4, along with details on how the RR ratio can be used to identify the optimal development path for WEC technologies. Figure 2 shows a flow chart providing a visual representation of this methodology and gives a brief indication of the input data for the LCOE and risk analyses. In order to demonstrate this methodology, two WEC devices were selected to be the focus of a number of case studies. These case studies were used to model different WEC design changes to investigate how the value for risk changed for each, enabling the optimal development path for different technologies to be identified. Details on each of these devices and case studies are given in Sections 2.2 and 2.3.

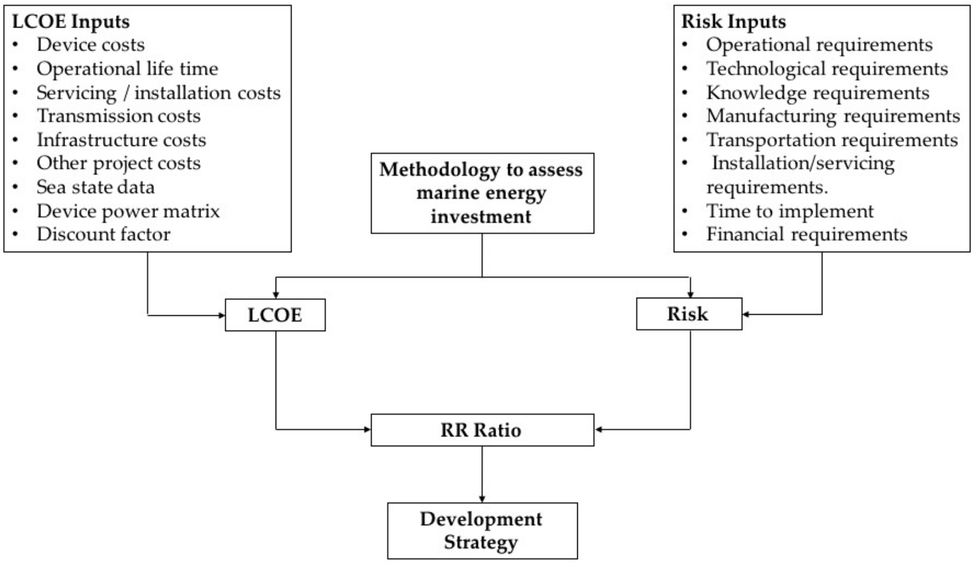

Figure 2. Flowchart of the proposed investment evaluation methodology.

2.2. Devices

2.2.1. Device Overview

Two different WEC devices were chosen to be the focus of the case studies used to demonstrate the methodology. The Pelamis P1 and the CorPower Ocean Wave Energy Converter were selected for the analysis due to the distinct differences between them. The Pelamis device was chosen as an example of a device that exhibits mature technologies used in a novel way to generate electricity from waves, and the CorPower device because it was considered as a device that uses novel technologies to generate electricity. By featuring both of these devices, a wide range of WEC technologies could be represented within the case studies.

2.2.2. PWP Pelamis P1

The Pelamis P1 is an attenuator-type device and uses a conventional hydraulic power take-off and electric generators to convert the hinging movement of the device as a wave passes into electricity. The device consists of a number of long cylinders connected together with hinges allowing relative movement in two planes between each. As the device points into the waves, and waves pass along the length of the device, relative movement between the cylinders pushes hydraulic rams. The oil flow created by the rams is smoothed using accumulators, then used to drive hydraulic motors, which in turn drive electric generators. A control system alters the flow of oil from the rams, to maximise the energy capture in small waves, or detune the device in storms [15]. The device is rated at 750 kW and is a good example of a large device exhibiting existing technology to produce electricity. The device was built only using standard parts and is a good representation of what is possible in marine energy using today's technology.

2.2.3. CorPower Ocean Wave Energy Converter

CorPower Ocean's Wave Energy Converter (WEC) technology belongs to the point-absorber category, with a heaving buoy on the surface absorbing energy from ocean waves while being connected to the seabed using a taut mooring line. It provides pneumatic pre-tension between the mooring and the buoy to enable a lightweight system. A novel phase control technology called WaveSpring widens the buoy's response bandwidth, and thereby also increases the power capture [16]. The absorbed wave energy is converted into electricity using a new type of mechanical direct drive PTO (power take off), located inside the buoy. A key component is a cascade gear box, capable of efficient conversion of linear-to-rotating motion with high durability. The cascade gear has a design principle similar to a planetary gear box, dividing a large load onto multiple small gears, arranged to allow conversion of linear-to-rotation motion in combination with a gear rack. A dual set of flywheels/generators provide power conversion and temporary energy storage for power smoothing. Generators and power electronics are standard components known from the wind industry, enabling well-known grid connection architecture. The units are designed to operate autonomously by a Programmable Logic Controller (PLC) located on the PTO, with an interface for remote control and data acquisition to shore over fibre and a radio-link [17].

2.3. Case Studies

2.3.1. Case Studies Overview

The Pelamis P1 and the CorPower WEC formed the basis for a number of case studies used to demonstrate the proposed methodology. Five case studies were selected to model a number of design changes to the two WEC devices described in the previous section. These design changes were chosen to represent alternative structural materials, PTO systems, control systems, and device scale (in terms of power rating), in order to determine which changes offered the best value for risk. These case studies allowed a direct comparison of value for risk between devices that exhibit mature and novel technologies. By ranking the value for risk of each design change it was possible to suggest an optimal development path for wave energy. Table 1 summarises each case study, detailing the design changes each intends to model, and the devices each was relevant to.

Table 1. Overview of case studies used to test methodology.

Case Study	Device	Design Change	Notes
1	• P1 750 kW • P1 375 kW • P1 1500 kW	Scale	Testing the effect of device scale on value for risk. Three Froude scaled variants of Pelamis P1.
2	• P1 750 kW • P1 750 kW Concrete • P1 750 kW GRP	Material	Testing the effect of structure on value for risk. Three structural variants of Pelamis P1.
3	• CorPower Ocean 300 kW (WaveSpring) • CorPower Ocean 300 kW (Latching) • CorPower Ocean 300 kW (Linear Damping)	Control regime	Testing the effect of control system on value for risk. Three variants of the Corpower WEC operating under different control regimes.
4	• CorPower Ocean 750 kW (Steel) • P1 750 kW	PTO	Comparing the PTO of the CorPower device to the PTO of the Pelamis P1. Mature vs. novel technology.
5	• CorPower Ocean 750 kW (GRP) • P1 750 kW	Material, PTO, control system	Comparing the value for risk of an up-scaled CorPower device (exhibiting many technologies to achieve cost reduction; material, PTO, control system) to the Pelamis P1 which represents more mature, less risky technologies.

2.3.2. Case Study 1: Scale Investigation

It was identified in Section 1 that developers are opting to reduce the cost of WECs through utilisation of economies of scale. It was therefore deemed appropriate to investigate how adjusting the scale of a device would alter the RR ratio. The first case study focused on determining how "value for risk" is affected by changes in the rated capacity of the device. Literature has identified that up-scaling a device has cost reduction potential; therefore, the effect of up-scaling must be the focus of a case study in order to make comparisons against other design changes [5]. A previous study provided suitable scaled cost and performance data for various scaled variants of the Pelamis P1 [7]. This case study investigates the LCOE and development risk of the standard 750 kW Pelamis P1, a half-size 375 kW Pelamis P1, and a double-size 1500 kW Pelamis P1. This range of capacities was comparable to the scaled capacities analysed in literature, providing confidence that the data was applicable for this analysis.

2.3.3. Case Study 2: Structural Material Investigation

SI Ocean [18] highlighted that alternative structural materials offer scope for significant cost reduction, allowing the optimisation of shape and weight of the prime mover, and improving device survivability and maintenance requirements. Traditionally steel has been used in the design of WECs; however, some developers are experimenting with the use of alternative materials such as GRP (glass-reinforced plastic) and concrete [2]. The second case study investigates the effect of changing the structural material on the "value for risk". A review of literature revealed a study into the feasibility of a number of different structural materials for the Pelamis P1 [19]. This study was used to analyse the LCOE and risk for a number of variants of the Pelamis P1 exhibiting different structural materials: a concrete Pelamis P1, and a GRP Pelamis P1, both rated at the nominal device output of 750 kW. Parametric modelling techniques were used to determine suitable costs for each based on data from the report.

2.3.4. Case Study 3: Control System Investigation

Another aspect of WEC design that has been highlighted as having potential to reduce the LCOE is the device's control system. Literature suggests that by using more sophisticated control systems, devices are able to extract more energy from the waves, and ultimately increase the annual energy yield from the device, resulting in a lower LCOE [18]. It was therefore deemed important to investigate the effects of changing the control system on the development risk and long-term LCOE. The CorPower Ocean WEC was used as the basis for this case study. Data was available for the power output and RMS power take-off force for this device when acting under three different control regimes: WaveSpring control, latching control, and linear damping control. Parametric modelling was used to establish a relationship between the PTO costs and the PTO force, in order to account for changes in device costs, as well as energy capture for the different control regimes.

2.3.5. Case Study 4: Power Take-off Investigation

It was deemed necessary to investigate how incorporating advanced power take-offs can affect the LCOE and development risk of a WEC. Improvement of power take-off systems was identified as another cost reduction opportunity, through increased energy capture from a device. The power take-off system is responsible for converting the motion of the prime mover, which itself is moved by the waves, into grid-quality electricity. The efficiency, reliability and survivability of the power take-off system were found to have an impact on the cost impact of a device. Hydraulic PTOs have been identified as commonplace within the industry; however, developers are experimenting with alternative technologies such as linear generators which could offer greater energy conversion efficiencies [18].

The fourth case study compares the power take-off of the Pelamis P1 and the CorPower Ocean WEC. The Pelamis P1 exhibits a PTO system made up of conventional hydraulic components whereas the CorPower Ocean device uses a bespoke cascade gearbox PTO. By comparing these two devices we can determine how the value for risk compares between a more conventional PTO (Pelamis P1) and a bespoke one (CorPower Ocean). To ensure results are comparable, the CorPower Ocean device was scaled up to the same rated capacity as the Pelamis P1, which was 750 kW. This study allows the comparison of a device with a PTO using conventional off-the-shelf components against a device that uses a bespoke PTO system. To keep the comparison fair between the Pelamis P1 and the CorPower Ocean device, the CorPower Ocean device was assumed to be made from steel, not GRP, as has been used in the 300 kW device. Parametric scaling was used to account for the change in device costs based on this material change. Switching the CorPower Ocean structural material to steel ensured that the comparison was between two steel structured WECs with different power take-off systems and principals of operation.

2.3.6. Case Study 5: Combined Technologies Investigation

Historical examples of the development of novel technologies show that the best features from a number of different iterations of a technology will evolve into a dominant design [20]. A case study was therefore chosen to evaluate the RR ratio for a WEC device exhibiting a combination of promising technologies. An up-scaled 750 kW CorPower Ocean WEC was determined to represent this device, exhibiting an innovative PTO, optimised structural material and control system, as well as being relatively large scale. This allowed the cost reduction potential and corresponding project development risk to be determined for a theoretical dominant design made up of the most promising technologies.

2.3.7. Deployment Capacities

It was determined that the LCOE should be based on a commercial deployment size of 100 MW, which is in line with the size of a commercial farm recommended by OES (ocean energy systems) [21]. Therefore, the LCOE and development risk for each case study was evaluated for a 100 MW farm.

2.4. LCOE Calculation

2.4.1. Overview

The LCOE was calculated using a procedure based on the process outlined by the Carbon Trust [22]. The LCOE is defined as the sum of the CAPEX (capital expenditure), OPEX (operational expenditure) and decommissioning costs associated with the generation, discounted to present day value, divided by the electricity generated to the grid throughout the technologies' operational life [21]. Equation (1) shows this, where *LCOE* is the levelised cost of electricity, *CAPEX* is the capital expenditures, *OPEX* is the operational expenditures, *D* is the decommissioning cost, *AEP* is the annual electricity production, *n* is the lifespan of the deployment and *r* is the discount rate. The proceeding sections will detail each of the inputs used for the LCOE calculation.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t} + \frac{D}{(1+r)^n}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \tag{1}$$

Equation (1) was used as the basis for the calculation, with capital, operational and decommissioning costs calculated for each device. These development costs were split up into a number of different cost components, each representing a proportional cost of the overall development, and were used to proportionate the cost of the device to the total development cost.

2.4.2. Cost Components

The costs of developing a wave energy converter can be broken up into a number of different categories. Based on a previous LCOE study of the Pelamis, it was determined that costs should be split up into the categories shown in Table 2, based on a similar LCOE study by O'Connor [7]. The study used scaling constants to allocate costs to different cost components as a proportion of a reference cost for the device. The scaling constants for each category are shown in Table 2. The cost factor is the proportion of the cost of the device (D) or the total initial costs (TIC) of the development, as indicated in Table 2.

The reference costs of both the Pelamis and CorPower Ocean WECs were obtained from the literature [19,23]. All costs used for the analysis were adjusted for inflation and converted into GPB. The reference cost used for each variant of the Pelamis P1 can be seen in Table 3. The cost data for the CorPower Ocean WEC is commercially sensitive and is not shown.

Table 2. Cost components for LCOE model obtained from literature [7].

Cost Component	Factor	Reference
Installation	0.33	D
Spare parts	0.02	D
Rent	0.02	D
Site investigation	0.02	D
Grid connection	0.05	D
Management	0.1	TIC
Decommissioning	0.1	TIC
Insurance	0.03	TIC
O&M	0.03	TIC

2.4.3. Scaling Costs

Parametric modelling was used to scale device costs with changes in rated capacity. This method was used by O'Connor in a previous LCOE analysis for the Pelamis P1 [7]. O'Connor used the assumption that as the rated capacity of the device increases, the cost per MW reduces to take into account the effects of economies of scale. His scaling constant of 1.25/MW was used if a device was halved in capacity, and 0.75/MW was used if a device was doubled in capacity. The scaling constants and reference cost for each device in the case studies can be seen in Table 3.

Table 3. Cost scaling factors for the devices analysed.

Device	Reference Cost (£)	£/MW	Scaling Factor	Scaled Cost (£)
750 kW	Pelamis P1	1,372,020	1	743,178
375 kW	Pelamis P1	1,372,020	1.25	743,178
1500 kW	Pelamis P1	1,372,020	0.75	2,058,030
750 kW	CorPower Ocean	N/A	0.625	N/A

2.4.4. Material Changes

Changing the structural material of the Pelamis P1 devices was assumed to only change the structural component of the device costs and not affect the device's performance. The cost and weight of the structural components for steel, concrete and GRP Pelamis P1 devices were given in a Pelamis P1 structural material review by OPD (ocean power delivery) [19]. Parametric modelling was used to relate the change in device weight (caused by changing the structural material) to the change in device cost. The difference in weight was also used to determine the increase or reduction in sand ballast that would be required for each device, which also affected the cost. The data used for this calculation was obtained from literature [19]. The reduction in reference cost for each structural variant of the Pelamis P1 is given in Table 4.

Table 4. Adjusted device costs for different structural configurations.

Device	Cost (Thousand £)	Reduction (%)
Commercial Steel P1	1332	2.9
Commercial Concrete P1	1294	5.7
Commercial GRP P1	1360	0.8

2.4.5. Grid Infrastructure Costs

Grid connection costs were kept constant for each different device in this study. Accurate cost data for the likely transmission infrastructure costs of the Belmullet test location in Ireland was available, and was therefore used to ensure costs and the LCOE were realistic [7]. The costs for the main components of the connection infrastructure are shown in Table 5.

Table 5. Grid infrastructure costs for pre-commercial and commercial arrays.

Costs	Commercial Deployment (Million £)
Onshore Cable	8.67
Offshore Cable	1.47
Onshore Substation	5.14
Offshore Substation	0.69
Total	**15.97**

2.4.6. Learning Factor

Literature has identified the importance of correctly accounting for the learning factor in the LCOE calculation to ensure that the cost reduction path for a given technology is accurately reflected, as this can have a large influence on the LCOE [24]. Mature technologies will reduce in cost slower than newer technologies due to larger amounts of installed capacity. The learning factor was used to model the long-term cost reduction potential for the device, and therefore was used to model the likely cost of the device after a previous deployment of 500 MW, which was considered to represent a mature technology. The learning factor is the ratio of the device cost after learning effects to the initial device cost, and was used to adjust the reference costs to take "learning by doing" into account.

Research has shown that there is a great deal of uncertainty as to what the learning rate for wave energy technologies should be. A wide range of learning rates, between 6% and 18%, have been suggested for technologies within the marine energy industry [24]. To account for early and mature technologies in this analysis, the range was split into high (12% to 18%) learning rates, for novel technologies, and low (6% to 12%) learning rates, for mature technologies, to reflect the differing learning rates of each.

2.4.7. Locations and Sea States

The choice of location in an LCOE analysis of wave energy is of great importance due to the vast difference in resources between different sites. Locations of high and low annual energy output were chosen for the LCOE analysis to give the possible range of LCOE depending on the deployment location. The location of high annual energy output was chosen to be the Belmullet test site in Ireland, and the location of low energy output was the Ionian Sea on the East Coast of Greece. Such vastly different areas of resources were selected in order to demonstrate how high and low resources affect the RR ratio. The sea state data used for each of these locations can be seen in Appendix A. This data was obtained from a study by O'Connor [7].

2.4.8. Power Matrices

The energy output of the devices was calculated from their respective power matrices, obtained from O'Connor [7]. The power matrix for the 750 kW Pelamis P1 device can be found in Appendix A. The power matrices used for the CorPower Ocean WEC under each different control regime cannot be displayed as they are commercially sensitive. Froude scaling was used to generate the power matrices of scaled devices. The Froude scaling procedure for power matrices was found to be outlined in the literature [7].

2.4.9. Availability

The availability of renewable energy technologies is of considerable importance when evaluating its LCOE. Availability is defined as the proportion of time that the device is available to generate electricity, and is affected by the reliability and maintenance requirements of a device. A study by O'Connor showed the availability values to be used for the chosen locations for each case study [25]. The numerical availabilities used are shown in Table 6.

Table 6. Availabilities used to determine LCOE of each device.

Location	Availability
Ireland	0.75
Greece	0.55

2.4.10. Control System Changes

Changing a device's control system has an impact on the overall energy captured from the sea, and the device's annual energy output and the LCOE. Changing the control system was also found to change the root mean square, or RMS, force on the PTO. Larger forces on a device require equipment to be stronger, increasing device costs [26]. Literature identified that PTO costs increased with the PTO force; therefore, parametric modelling was used to model this, with the cost increasing in accordance with the scaling values found in Table 7, which were obtained from a CorPower Ocean report [23]. The cost of the PTO was assumed to be directly proportional to the PTO force. The force values are commercially sensitive and have been excluded from the table.

Table 7. PTO force ratios used to scale PTO and mooring costs.

Control Regime	PTO Force Ratio
Linear Damping	1.24
Latching	4.27
WaveSpring	1

2.4.11. Discount Rate

A number of different discount rates have been used in the past to model the LCOE for wave energy [27,28]. There is recognised uncertainty over the value of the discount rate that should be used to model the costs of wave energy, between 8% and 15% [24]; therefore, the range of possible values was used as an input to a Monte Carlo simulation to account for the uncertainty.

2.4.12. Validating the Model

To validate the model, the LCOE of the standard Pelamis P1 device at both locations was compared against the values calculated by O'Connor [7]. The comparison of results can be seen in Table 8. In Ireland, the O'Connor model differs from the new model by ~12%. This was determined to be acceptable as it was within the range of most probabilistic outcomes so the models were considered to be in agreement. This shows that the LCOE model described is realistic and can produce accurate results. LCOE data for the CorPower Ocean device was not available as it was commercially sensitive; therefore, the LCOE result for the CorPower Ocean device could not be validated.

In Greece, the models differ by a greater margin, with O'Connor's model giving an LCOE about 10% lower than the P10 result from the proposed model. It should be noted that an exact comparison between the two models was not possible due to limited data being supplied in the literature. The O'Connor model accounts for a 1 MW Pelamis P1 at Ireland, whereas this model accounts for a 750 kW device. Furthermore, the O'Connor model did not account for the effects of learning by doing in the same way as it is proposed in this study; therefore, we should expect some slight discrepancy between results. Ultimately, the new LCOE model was determined to give results within the ballpark ranges of the validation case, and was considered suitably accurate for this analysis.

Table 8. Comparison of LCOE results to validate the presented LCOE model.

LCOE Calculation	Ireland	Greece
O'Connor (£kWh)	0.18	0.75
Hutcheson (£kWh)	0.14 to 0.18	0.83 to 0.98
Difference (%)	−28.6 to 0	9.6 to 23.5

2.5. *Risk Analysis*

2.5.1. Overview

Risk was considered to be composed of two elements: design difficulty and resources required. A number of metrics were devised in order to quantify the risk of each of these categories, and then the total risk was obtained by summing the design difficulty risk and the resource risk. This section justifies the selection of each risk metric falling within these two categories by presenting issues identified in wave energy literature. A breakdown of the scoring criteria for each metric is also given. A more detailed justification of how each device was scored for each metric is presented in Appendix B.

As discussed in Section 1, qualitative risk assessments of marine energy have been conducted in the past, as shown by the OPERA report which uses DNV GL standards to categorise the risk of WEC developments as either "high" or "low" [11]. This work takes risk assessment one step further and uses a qualitative approach to quantify the risk of a number of different developments. This was done by considering the design difficulty risks and resource risks as recommended by Moody [14]. It should be noted that the design difficulty risk was analysed separately for the device structure, control system and PTO system, to isolate the risks of different technologies. The total device design difficulty risk was calculated by averaging the risks of the individual sub-systems. The resource risk was deemed to be appropriately allocated to the device as a whole, instead of for each different sub-system.

In Section 1 it was explained how risk should be split into two categories, "design difficulty" and "resources". Literature assigned different weightings to different metrics within the design difficulty and resources categories [14]. As the metrics used in this analysis were derived from each of the metrics detailed in the literature, the same weightings were used to apply weight to each. The weighting applied to each metric is summarised in Tables 9 and 10. By evaluating each development according to these risk metrics, the risk attributed to each was determined.

Table 9. Marine energy–specific design difficulty metrics.

Design Difficulty Metrics	Marine Energy Metric	Category Weighting
Design type	• How scalable is the sub-system? • How well suited is the technology to dealing with the loading placed upon it? • How efficiently does the technology perform its prime function? • How well suited is the technology to the marine environment?	1.5
Knowledge complexity	• How well understood is the technology exhibited in the sub-system?	1
Steps	• How many manufacturing steps are required to take the sub-system from the final engineering design to a fully operational device?	1
Quality	• How well established is the reliability of the technology? • What levels of maintenance does the technology require?	1
Process Design	• How manufacturable is the technology used within the sub-system?	0.5

Table 10. Marine energy–specific resources metrics.

Resources Metrics	Marine Energy Metric	Category Weighting
Cost	• What is the total cost of a pilot device deployment? • What learning investment is required to develop the technology?	1.5
Time	• How long does the device take to manufacture? • How long does the device take to install in its deployment location?	1
Infrastructure	• What are the infrastructure requirements to manufacture/assemble the device? • What are the infrastructure requirements to transport and install the device? • What are the infrastructure requirements to service the device?	1

2.5.2. Design Difficulty Metrics

How Scalable Is the Sub-System?

This metric is designed to assess the scalability of each sub-system, which was identified as a development risk in the literature. The literature identifies that small-scale devices are required to drive innovation and cost reductions through learning by doing at a sensible development cost [5]. Furthermore, it highlighted that once the dominant design emerges, it will be up-scaled to take advantage of the economies of scale until it is commercially competitive [5]. It is clear, therefore, that technologies used to develop WECs should be scalable, from small demonstration sizes to the size a full commercial device is likely to be. Wave Energy Scotland also recognises scalability as an important feature of a potential innovative WEC power take-off [26]. A risk is posed to the developer, therefore, if the technology they develop will not scale up to commercial sizes.

This metric was considered to fall under the design-type metric within the design difficulty category. A quantitative assessment of scalability was thought to be too specific for the wide range of possible WEC concepts at this stage in the industry's development. Instead, risk was assigned qualitatively using engineering judgement to analyse the scaling potential of the technology. The risk was categorised by two plausible extremes: the highest risk score was attributed to a technology that cannot be scaled without a breakthrough in engineering technology, and the lowest risk was attributed to technologies that are infinitely scalable across the range of likely sizes of a WEC. Intermediate situations were created to address scalability risks between the two extremes. The criteria created to assign risk to this metric can be seen summarised in Table 11.

Table 11. Risk score criteria for technology scalability metric.

Score	Description
1	The technology can be easily scaled, to any likely scale without significant redesign of the sub-system.
2	The technology can be easily scaled without significant redesign to a point; however, for very large devices a significant redesign would be required.
3	The technology does not lead itself to being scaled in its current configuration, unless a significant re-design is carried out.
4	The technology cannot be scaled from its current form without a significant engineering breakthrough in the technology.

How Well Suited Is the Technology to Dealing with the Loading Placed upon It?

Literature identified that a large part of the risk within the wave energy industry is the survivability of the device. An SI Ocean report [4] highlights that survivability is an aspect of WEC design that requires attention and poses a risk to a developer. It was recognised that only a handful of devices had achieved "extensive levels of operational hours" and that "a lot of innovation is required in this area" [4]. The hazard is that devices may not survive the harsh marine environment, leading to a costly failure at sea. The risk is therefore the extent to which the device is expected to survive in the ocean waves. Wave Energy Scotland included "suitability for marine environment" in the evaluation criteria for their PTO call guidance initiative [26]. This was deemed to be another aspect of survivability that contributes to project risk.

A number of different loading cases were identified as affecting the survivability of the device; three particular loading scenarios were selected as being of importance: extreme loading, fatigue and bucking resistance. These were used by PWP (Pelamis Wave Power) in a design report for the Pelamis P1 and were considered to be applicable to this study [19]. Engineering judgement based on the evidence available was therefore used to determine the suitability for the particular sub-system for each of the loading scenarios on a case by case basis. Each metric was scored either good (score 1), average (score 2), or poor (score 3), and the combined risk score of each was used to determine the overall survivability of the sub-system in accordance with Table 12.

Table 12. Risk score criteria for device survivability.

Score	Description
1	Good survivability. Combined score 3 or 4
2	Average survivability. Combined score 5 to 7
3	Poor survivability. Combined score 8 or 9

How Efficiently Does the Technology Perform Its Prime Function?

Device efficiency was also highlighted as an area of risk. This metric was designed to address the risks posed to the developer through evaluation of the efficiency of the technologies used within the design. Wave Energy Scotland recommends that efficiency is an important factor with regards to PTO development [26]. Devices that are less efficient pose a higher risk due to inferior performance compared to another, more efficient technology. The hazard, therefore, is that a technology with a low theoretical maximum efficiency may not be competitive against other technologies in the long run, resulting in the technology becoming obsolete. There is, therefore, a risk posed to developers if they choose to develop a technology with a low theoretical efficiency which is unlikely to emerge as the dominant design. As each sub-system performs a different function within the device, the scoring system was tailored for each.

The prime function of the PTO was identified as kinetic to electrical energy conversion; therefore, the efficiency measure was to determine the kinetic to electrical conversion efficiency [26].

The control system's primary function is to maximise energy capture from the sea; therefore, the device's maximum theoretical capture width was selected as the metric for evaluation. The maximum theoretical capture width for a number of different WEC types was given in the literature [15]. Values were expressed as a proportion of the oncoming wavelength (λ). Devices with a high theoretical capture width were considered to be lower risk than those with a smaller capture width, as seen in Table 13.

Due to the dual purpose of the structure—a dynamic prime mover and a strong structural frame onto which all the sub-systems mount—a specific efficiency metric is unsuitable to evaluate this sub-system. It was determined that the structural efficiency should be qualitatively assessed on a case by case basis using a number of different metrics that were considered to be attributed to structural efficiency. These metrics were chosen to be: rigidity, bucking resistance and ballast requirement as derived from PWP's Pelamis P1 structural design report [19]. Each of these metrics was scored as either good (score 1), average (score 2), or poor (score 3), and the combined risk score of each was used to determine the efficiency of the device's structure. The efficiency risk scoring criteria for each sub-system are shown in Table 13.

Table 13. Scoring criteria for evaluation of efficiency metric.

System	Metric	1	2	3
Structure	Rigidity, buckling, ballast requirement	3 or 4	5 to 7	8 or 9
PTO	Energy conversion efficiency of entire system	>90%	>50%	<50%
Control	Maximum theoretical capture width (in terms of oncoming wavelength)	>0.5 λ	0.5 λ to 0.25 λ	<0.25 λ

How Well Suited Is the Technology for the Marine Environment?

Wave Energy Scotland highlighted that a WEC development risk is the suitability of the technology for the marine environment [26]. This metric assesses the suitability of the technology with respect to aspects such as water damage, corrosion and bio-fouling. It addresses the hazard that a technology that is not well suited to the marine environment is unlikely to emerge as the dominant design. The risk is therefore the extent to which a technology is suited to the marine environment; a technology that is well suited is low risk, and one that is not well suited is high risk.

The scoring criteria were designed to represent the most likely range of possibilities for a technology's suitability to the marine environment. The risk categories can be seen in Table 14. A qualitative assessment of each particular technology featured within the case studies was used to allocate risk to each sub-system.

Table 14. Suitability for marine environment risk evaluation criteria.

Score	Description
1	Technology well suited to the marine environment, will not corrode or bio-foul in sea water in its standard untreated form.
2	The technology is not well suited to the marine environment in its standard form but can be chemically treated to protect it.
3	The technology is not well suited to the marine environment and cannot be treated to protect it. It can be sealed in a protective casing.

How Well Understood Is the Technology Exhibited in the Sub-System?

The state of understanding of a technology was highlighted in the literature as a potential development risk. Literature suggests "knowledge complexity" as a project development risk [14]. The logic behind monitoring this metric is that if a design relies on engineering knowledge that very few people possess or have the means to discover, a large amount of risk is added to the development due to the need to employ or contract this specialist knowledge. On the other hand, a design that requires only basic engineering knowledge that many people possess is inherently less risky. Marine energy research has identified that novel, less well-understood technologies need to be adopted to drive the LCOE down, and has identified that these technologies pose a higher development risk compared to more conventional, better-understood technologies [4]. It was therefore determined that the extent to which a WEC technology is understood should be used to measure development risk. Low risk was attributed to a technology which is well understood by many in a commercial sense, and high risk was attributed to a technology which is only understood in a research sense, and has not reached commercialisation. The criteria used and the corresponding scores to assign risk for this particular metric can be seen in Table 15.

Table 15. Risk scoring criteria for knowledge complexity metric.

Score	Description
1	The technology is well understood by many and has been commercialised.
2	The technology is well understood by only specialists and has been commercialised.
3	The technology is understood only by specialists in a research sense and has never been commercialised.

How Well Established Is the Reliability of the Technology?

Literature revealed that the reliability of a technology has a substantial effect on the development risk of a WEC due to the uncertainty in the maintenance requirements it introduces. The other important aspect of O&M (operation and maintenance) is unplanned maintenance, which is determined by the reliability of the technology. SI Ocean [4] highlight that the reliability of a technology should be used to allocate risk to a WEC development. The hazard regarding the reliability of a WEC is that if the reliability of the technology is not well understood prior to deployment, the developer cannot be certain about the maintenance schedule, resulting in unknown and potentially high maintenance costs. The risk was determined to be the degree to which the reliability of the technology is understood. This metric assesses the risk associated with the reliability uncertainty of the chosen technology. A logical engineering assessment approach was used to categorise different levels of reliability uncertainty to obtain the reliability risk for a given technology. Technologies with well-understood reliability traits scored a low risk, and technologies with a poor understanding of reliability scored a high risk. These categories can be seen in Table 16.

Table 16. Scoring criteria for technology reliability metric.

Score	Description
1	Reliability of the technology is very well understood with extensive data to prove it.
2	Reliability of the technology is known to an extent, with some test data/operational data.
3	Reliability of the technology is unknown, with no reliable test data.

What Levels of Maintenance Does the Technology Require?

Maintenance was identified as an important contributor to the risk of a WEC development due to its high predicted costs. The literature revealed that maintaining and servicing marine energy devices poses considerable risks due to the unpredictability of the sea and thus when the device may be available to access for routine and unplanned maintenance [4]. A study by O'Connor details how varying degrees of access to WECs changes the device availability, directly impacting the energy capture from the site, and ultimately the LCOE [25]. From the results of this study we can deduce that to maximise the availability of a WEC, planned maintenance should be minimised. Therefore, it was deemed appropriate to create a metric that would assess the requirement for the maintenance of a technology. The hazard with a device that requires much planned maintenance is that due to the unpredictability of the sea, the accessibility is unknown and it is not certain how the availability will be affected. By reducing the planned maintenance, the uncertainty on how maintenance will affect availability is reduced. The risk should therefore be evaluated based on the extent of the routine maintenance that is required. This metric reflects the risk associated with a given technology due to the levels of maintenance it will require over its lifetime, as well as the design life of the technology. A technology that requires regular maintenance or replacement due to a short design life is inherently riskier than a technology whose technology will last the lifetime of the device with little or no maintenance. High- and low-risk maintenance cases were considered for the sub-systems of a WEC and used to create the categories seen in Table 17. Low risk was attributed to technologies which are maintenance-free, and high risk to those which require much maintenance.

Table 17. Risk criteria for maintenance metric.

Score	Description
1	The technology is designed to be maintenance-free for the lifetime of the device.
2	The technology requires only light maintenance at regular intervals. Maintenance conducted offshore.
3	The technology requires replacement/overhaul once throughout the lifetime of the device. Maintenance carried out on shore.
4	The technology is designed to need replacing/overhauling several times throughout the device's life span. Maintenance carried out on shore.

How Many Manufacturing Steps Are Required to Take the Sub-System from the Final Engineering Design to a Fully Operational Device?

This metric is designed to reflect the risk the developer adds to the project through the number of steps the manufacturing process requires. The literature suggests that the number of manufacturing steps affects the design difficulty risk [14], attributing a higher risk to a project that requires more manufacturing steps. SI Ocean [4] reveals that the development of a supply chain is required to spread manufacturing risk throughout the industry, instead of placing it on just a single developer. This identifies that by reducing the number of manufacturing steps that a developer must take to produce a device, the developer is exposed to less risk. The hazard with numerous manufacturing steps is that at each step, there is a chance that something may go wrong, for example supply or production problems that cause a delay or affect the quality of components. We can therefore determine that devices that require more manufacturing steps pose a higher development risk than those that require fewer.

The simplest and lowest-risk manufacturing process for a WEC was determined to be a system which could be purchased complete from supplier and installed into the WEC, requiring only minimal connections to the other sub-systems within the device. The riskiest process was determined to be a process which required several different manufacturing steps to produce components within the assembly, before a complex process of integrating the components into an assembly before installation into the device. Evaluating this metric required a qualitative analysis of the individual sub-system and the way in which it is manufactured and installed within the device. The scoring categories can be seen in Table 18.

Table 18. Criteria for scoring manufacturing steps risk.

Score	Description
1	Off-the-shelf assembly fits straight into device (one step).
2	Off-the-shelf components assembled into sub-system, then installed in device (two steps).
3	Bespoke components requiring a few manufacturing steps before being assembled into the sub-system and then being installed into the device (three steps).
4	Bespoke components requiring many manufacturing steps before being assembled into the sub-system before being installed into the device (four or more steps).

How Manufacturable Is the Technology Used within the Sub-System?

This metric is designed to assess the technical complexity of the manufacturing process, which was identified as a risk in the systems engineering process. The literature highlighted that manufacturing devices in large quantities using complex processes is substantially riskier than manufacturing devices in smaller volumes with simple processes, and this must be reflected in the risk analysis [14]. This differs from the 'steps' metric because instead of attributing risk to the number of manufacturing steps required to produce a device, the process design accounts for the risk due to the increased difficulty of the design work due to the need to design a complex manufacturing process. The hazard associated with this metric is that increased complexity introduces more areas where problems can occur, which could lead to cost overruns and project failure. This metric was deemed to be applicable to the development of WEC devices without modification. The manufacturing complexity and quantities produced by the manufacturing process should therefore be used to assign risk to each device's process design.

More risk is attributed to a device or sub-system that requires complex manufacturing processes requiring specialist equipment. It is also suggested that the process design risk increases with increased production volumes. The sub-systems were evaluated for their process design based on the production techniques and volumes likely for the manufacture of a 100 MW farm in a matured wave energy market. Devices with a rated capacity of 0.5 MW or less were considered to be manufactured in high volumes, those between 0.5 MW and 1 MW were considered be manufactured in moderate volumes, and those greater than 1 MW were considered be manufactured in low volumes. Low risk was attributed to manufacturing processes that require the use of standard, well-established technologies with low production numbers. High risk was attributed to complex manufacturing processes with high volumes of production. The scoring criteria for this metric can be seen in Table 19.

Table 19. Risk score criteria for technology process design metric.

Score	Description
1	• Straightforward, well-established manufacturing processes, using conventional technologies, with small production numbers.
2	• Straightforward manufacturing process using advanced but well-established technologies in small production volumes. • Straightforward, well-established manufacturing processes, using conventional technologies, with moderate production numbers.
3	• Complex manufacturing process using novel manufacturing technologies in small production volumes. • Straightforward manufacturing process using advanced but well-established technologies in moderate production volumes. • Straightforward, well-established manufacturing processes using conventional technologies, with large production volumes.
4	• Complex manufacturing process using novel manufacturing technologies in moderate production volumes. • Straightforward manufacturing process using advanced but well-established technologies in large production volumes.
5	• Complex manufacturing process using novel manufacturing technologies in very large production volumes.

2.5.3. Resources Metrics

What Is the Total Cost of a Pilot Device Deployment?

The literature highlighted that a large proportion of the "resource" risk is accounted for by project costs [11]. Higher costs translate directly to higher risk. SI Ocean [4] highlights that developers expose themselves to less risk if they develop cheaper, small-scale technologies. It was therefore deemed important to establish which costs pose risks to a developer when pursuing a WEC development. Systems engineering best practices recommend that first-of-a-kind technologies should be deployed on a small scale in order to minimise the financial resources required to prove them [10]. Put in a marine energy context, this indicates that the cost of the pilot deployment should be used to assess the risk, as it represents the cost to the developer to prove the technology.

It was determined that the capital cost of the pilot scheme should be used to evaluate this particular risk with regards to the WEC developments. The pilot scheme was determined to be the deployment of a single full-scale device with a grid connection. Predicted pilot deployment costs for wave energy were used to categorise the risk associated with a given deployment capital cost. This particular risk simply increases with the greater costs of the pilot device. The categories used for scoring this metric can be seen in Table 20 Data from the LCOE analysis was used to determine what the initial project costs for each device were, and hence the risk.

Table 20. Risk categories for pilot deployment costs.

Score	Cost (Million £)
1	<5
2	5 to 10
3	10 to 15
4	15 to 20
5	20 to 25
6	25 to 30
7	30 to 35
8	35 to 40
9	>40

What Learning Investment Is Required to Develop the Technology?

The literature highlighted that another important cost-related metric was the learning investment [29]. This is the amount of money required to drive the cost of wave energy down to the levels of offshore wind. Developing a device that requires a lower investment to develop it to commercial competitiveness clearly poses less risk than a device that requires a larger investment. Literature presented the range of estimated learning investments for the industry [24].

Based on the extent of mature and novel technologies exhibited in a device, appropriate learning rates were chosen for the devices. These were used to calculate the total learning investment of a device, and hence allocate a risk score for this particular metric. The learning investment was calculated based on a hypothetical formative development phase of 1000 device deployments. This number was deemed to be appropriate as it was found to be used in a similar study [24]. The scoring criteria for this metric can be found in Table 21.

Table 21. Installation time risk categories.

Score	Cost (Million £)
1	<1
2	2 to 3
3	2 to 3
4	3 to 4
5	4 to 5
6	5 to 6
7	6 to 7
8	7 to 8
9	8 to 9
10	9 to 10
11	>10

How Long Does the Device Take to Manufacture?

It was also highlighted that to be competitive with offshore wind, WEC devices will have to be producible at a similar rate to offshore wind turbines. Time to manufacture was identified as a risk. SI Ocean [4] highlights the need for the capacity to be deployed quickly in order to drive industry growth and secure the backing of the supply chain. Furthermore, we have identified that wave energy must be competitive with offshore wind. The hazard is that the production rates of capacity cannot keep up with offshore wind, resulting in marine energy being uncompetitive. Hence, it was determined that the rate at which WEC capacity can be manufactured, in relation to offshore wind, should be used as a measure of risk. This metric is, therefore, designed to assign risk to a device based on the time required to manufacture it.

The time taken to manufacture offshore wind turbine capacity was used as the benchmark for the evaluation of this metric. Literature revealed that it takes Siemens 300 h to manufacture an offshore wind turbine (2014) [30]. No details were available as to what size of this turbine the figure referred to; however, based on the rated capacity of Siemens' offshore wind turbines, it was assumed that this would be for a turbine capacity of 3.6 MW. The reference manufacturing time was therefore determined to be 83 h/MW. For the purposes of this analysis, it was assumed that the manufacturing time scaled linearly with changes in rated power. An arbitrary value of 20% was chosen to calculate the low- and high-risk manufacturing times based on the reference value. The manufacturing time for different devices was determined through a qualitative assessment of each. The scoring criteria for this metric can be found in Table 22.

Table 22. Time to manufacture risk criteria.

Score	Description
1	Manufacturing time is under 66 h/MW
2	Manufacturing time is between 66 h/MW and 100 h/MW
3	Manufacturing time is over 100 h/MW

How Long Does the Device Take to Install in Its Deployment Location?

Another time-related risk was determined to be the time to install. Indeed, the literature has revealed that the time it takes to install a device is an important issue due to the limited weather windows available on the seas [4]. Research has shown that the number of weather windows available is dependent on the time required for the deployment and the significant wave height the installation can occur in [25]. If a device takes a significant length of time to install, in a year, there are likely to be fewer weather windows large enough to install the device, resulting in downtime while waiting to install the device, which will ultimately affect the electricity production and the LCOE of the deployment. If a device has a shorter installation time, the number of weather windows that it can be deployed in is large. A device with a short installation time therefore poses a low risk to a project compared to a device that requires significantly more time to install. The time and maximum wave height for installing the device were used to categorise the installation risk, as seen in Table 23.

Table 23. Installation time risk categories.

Score	Description
1	At least 6 h and up to 2 m wave height
2	At least 6 h and up to 1.5 m wave height At least 12 h and up to 2 m wave height
3	At least 24 h and up to 1.5 m wave height At least 12 h and up to 1.5 m wave height At least 24 h and up to 2 m wave height
4	At least 6 h and up to 1 m wave height At least 12 h and up to 1 m wave height
5	At least 24 h and 1 m wave height

What Are the Infrastructure Requirements to Manufacture/Assemble the Device?

The literature highlighted that the infrastructure required to manufacture the device accounts for a proportion of the project risk. The availability of manufacturing locations was determined to be a risk when developing a WEC. Literature revealed a report by PWP that used the availability of manufacturing locations as a metric when evaluating the suitability of a structural material for the

Pelamis P1 [19]. Very large devices are likely to need specialist facilities for manufacturing, such as ship building yards, due to an inability to transport large devices significant distances over land. The hazard associated with the availability of manufacturing locations is that very specialist facilities may not be available when the developer requires them, resulting in costly delays, or requiring the developer to construct their own facilities. Risk should therefore be measured based on the availability of the manufacturing facilities required to make the device.

This metric accounts for that risk by categorising the infrastructure requirements for the manufacturing process. Engineering judgement and available information for each device was used to assess the manufacturing requirements for various technologies that could be used in marine energy. This assessment was used to derive a number of risk criteria, which can be seen in Table 24. Low risk was attributed to devices that require minimal amounts of manufacturing infrastructure, and high risk to devices that require significant manufacturing infrastructure resources.

Table 24. Manufacturing infrastructure risk categories.

Score	Description
1	Existing and widely available facilities can be used to manufacture the device. These include land-based workshops that can be used to assemble the technology.
2	Existing and widely available port facilities can be used to manufacture the device. Specially built facilities are required to manufacture the device. Facilities can be inland.
3	Specially built facilities are required to manufacture the device. Facilities must be on the shore so the device can be deployed straight to the sea.

What Are the Infrastructure Requirements to Transportation and Install the Device?

Literature identified that transportation and installation can pose a to risk to a WEC project. SI Ocean reveals that installation and retrieval pose significant infrastructure-related development risks; their "Gaps and Barriers" report highlights that installation and retrieval can amount to a significant proportion of project costs due to the high cost of vessels required for deployment [4]. It notes that the cost for vessels can vary depending on the requirements of the device. Large vessels such as jack-up barges from the oil and gas sector were noted as being considerably expensive as costs are "dominated by the oil and gas spot market" with which "renewables cannot compete" [4]. It was therefore determined that the vessels required to install a device should contribute to the overall development risk of a device. The hazard here being that the cost of hiring vessels for installation and maintenance fluctuates with the oil and gas market, resulting in uncertainty in O&M costs. Smaller, more common vessels should account for low infrastructure risk, and large expensive vessels for high risk.

This metric categorises the transportation and installation risks for a device, and assigns a risk score, based on a qualitative assessment. Installation was split up into two different parts. Over-land transportation, and sea transportation. The over-land transportation risk was split into three scenarios: can be transported using conventional lorries (e.g., shipping containers), can be transported using only specialist oversized lorries (moderate risk), and, finally, cannot be transported by road (high risk). The sea transportation risk was split into two scenarios: can be transported using small and cheap non-specialist vessels (low risk), and the device requires specialist and therefore expensive vessels for transport (high risk). Three categories were made to categorise the risk: minimal (scores 1), moderate (scores 2) and substantial (scores 3), as seen in Table 25.

Table 25. Risk categories for evaluating transportation and installation infrastructure metric.

Score	Description
1	• Devices can be transported by road using conventional lorries. Installation requires only small non-specialist vessels to tow the device into position.
2	• Devices can be transported by road using conventional lorries. Installation requires specialist vessels to transport and install the technology. • Devices require specialist lorries to transport by road. Installation requires only small non-specialist vessels to tow the device into position.
3	• Device cannot be transported by road, and must be deployed into the sea. Installation requires specialist vessels to transport and install the technology.

What Are the Infrastructure Requirements to Service the Device?

The literature highlighted that risk is attributed to the infrastructure required to service the device. A report by SI Ocean [4] also highlights that servicing infrastructure can have a large impact on the feasibility of a WEC development; therefore, a number of categories were created to categorise the service infrastructure risk of a particular device, which can be seen in Table 26. Devices that require significant infrastructure for servicing, such as the requirement for specialist vessels or returning the device to the shore for servicing, were allocated a high risk score, and those with minimal infrastructure requirements were allocated a low risk score. Again, a qualitative assessment of each device was used to determine its risk score.

Table 26. Service infrastructure risk categories.

Score	Description
1	Small non-specialist vessels required to do offshore maintenance.
2	Small non-specialist vessels required to retrieve the device for maintenance. Specialist vessels required to do offshore maintenance.
3	Specialist vessels required to retrieve the device for onshore maintenance.

2.6. RR Ratio

The final stage in the analysis was to compare the ratio of the risk and the LCOE to determine the "value for risk" of each specific design change. The ratio was defined as the LCOE divided by the development risk, as detailed in Section 2.4.1, and has the units £/kWh. This ratio will be referred to as the RR ratio hereafter. The equation for the RR ratio can be seen in Equation (2). By dividing the LCOE by the risk, we can determine the contribution to the final LCOE that each risk point holds. For a given risk, a lower RR ratio indicates that the LCOE of the development will be lower, and hence a lower RR ratio indicates a more efficient use of risk to reduce the LCOE. By comparing the RR ratio of various design changes, it is possible to identify which design changes utilise risk best to reduce the LCOE. This information can then be used to determine and rank the "value for risk" of various design changes to determine the optimal technology development path for wave energy devices.

$$RR = \frac{\text{LCOE}}{\text{Risk}\,(\text{design difficulty, resources})} \tag{2}$$

3. Results and Discussion

3.1. LCOE Analysis

The LCOE model was run for both locations, Ireland and Greece, for each device featured in the case studies. From this analysis the LCOE of each was obtained. The results showed that the LCOE of the devices at Greece was significantly higher than that for Ireland, causing these projects to be unfeasible. The focus of the analysis was therefore Ireland, where the lower LCOE suggested that devices in this location could be competitive. The LCOE calculated for each case study can be seen in Table 27.

Table 27. LCOE results from the analysis for Ireland.

Case Study	Device	LCOE (£/kWh)
1	P1 750 kW	0.16
	P1 375 kW	0.149
	P1 1500 kW	0.182
2	P1 750 kW Concrete	0.152
	P1 750 kW GRP	0.159
3	CorPower Ocean 300 kW (WaveSpring)	0.115
	CorPower Ocean 300 kW (Latching)	0.409
	CorPower Ocean 300 kW (Linear Damping)	0.359
4	CorPower Ocean 750 kW (Steel)	0.136
5	CorPower Ocean 750 kW (GRP)	0.135

3.2. Risk Scores

Each case study was analysed and assigned a risk score using the methodology described in Section 2.2. Table 28 shows the risk scores assigned for each device analysed in the case studies.

Table 28. Risk scores for case study devices in Ireland.

Case Study	Device	Design Difficulty	Resources	Combined Risk
1	P1 750 kW	2.73	1.7	4.43
	P1 375 kW	2.8	1.63	4.5
	P1 1500 kW	2.66	1.93	4.6
2	P1 750 kW Concrete	2.86	1.60	4.67
	P1 750 kW GRP	2.98	1.44	4.7
3	CorPower Ocean 300 kW (WaveSpring)	3.53	1.53	5.2
	CorPower Ocean 300 kW (Latching)	3.53	1.78	5.45
	CorPower Ocean 300 kW (Linear Damping)	3.53	1.64	5.33
4	CorPower Ocean 750 kW (Steel)	3.43	1.86	5.3
5	CorPower Ocean 750 kW (GRP)	3.47	1.84	5.44

3.3. Monte Carlo Analysis

A Monte Carlo analysis was used to statistically determine the most probable results from the wide range of input data for the LCOE analysis. Due to the wide range of possible input values for the LCOE calculation, a robust treatment of uncertainty must be applied to produce meaningful results. The Monte Carlo analysis was identified as a suitable method for determining the range of probable results from a model. The Monte Carlo analysis is a tool used within statistics to estimate the final outcome of a problem. The analysis takes inputs that vary randomly or within a known probability distribution, and outputs the problem solution as a probability, which is more useful to know than simply a sensitivity analysis or best/worst case analysis. The Monte Carlo simulation is a very reliable calculation and is based on two sound mathematical theorems, the central limit theorem and the law of large numbers [31]. Monte Carlo simulations are used widely in engineering, business and sciences where an estimate must be made under conditions of uncertainty [24].

Curve fitting functions were used in Matlab in order to establish which probability distribution best fit the data. The P10, P90, mean, standard deviation and coefficient of variation were then calculated for each deployment in each case study. These results have been summarised for Ireland in Table 29. The results show that the coefficient of variation for each case study is consistently around the 10% mark. This variation was considered to be low enough to indicate accuracy within the Monte Carlo analysis, with a narrow range of data providing confidence in the final range of LCOE values.

Table 29. LCOE results from the Monte Carlo simulation for Ireland (£/kWh).

Case Study	Device	P10	P50	P90	Std. Dev.	Coefficient of Variation
1	P1 750 kW	0.139	0.16	0.183	0.017	10.6%
	P1 375 kW	0.128	0.149	0.171	0.018	12.1%
	P1 1500 kW	0.158	0.182	0.206	0.013	6.3%
2	P1 750 kW Concrete	0.131	0.152	0.173	0.016	10.5%
	P1 750 kW GRP	0.138	0.159	0.182	0.017	10.7%
3	CorPower Ocean 300 kW (WaveSpring)	0.099	0.115	0.134	0.013	11.3%
	CorPower Ocean 300 kW (Latching)	0.347	0.409	0.473	0.047	11.5%
	CorPower Ocean 300 kW (Linear Damping)	0.306	0.359	0.414	0.04	11.1%
4	CorPower Ocean 750 kW (Steel)	0.118	0.136	0.154	0.014	10.3%
5	CorPower Ocean 750 kW (GRP)	0.117	0.135	0.154	0.014	10.4%

3.4. Risk vs. Reward

Moody recommended plotting the design difficulty risk against the resources risk to help to classify how one device stands against another [14]. A plot of the design difficulty against the resources required can be seen in Figure 3. By examining this plot, we can categorise developments relative to each other using the quadrants shown in Figure 2. We can see that the 1500 kW Pelamis P1 exhibits traits of the "seven wonders of the ancient world' category", indicating that, relative to other developments, this device poses a low design difficulty risk and high resource risk. The 300 kW device was determined to place in the "Star Wars" quadrant due to its relatively high design difficulty risk and low resource risk. Both up-scaled CorPower Ocean devices were considered to be representative of the moon landings category as these exhibited both high design difficulty and resources risk. The remainder of devices were considered to fall into the "consumer products" category, indicating that these developments were the most feasible. Categorising the deployments in this way aided identifying the projects which it was expected a single developer could take on, and which projects would require several developers to work together. Devices that were placed in the "moon landings" and "seven wonders of the ancient world" categories were considered to be projects that only very large developers, or groups of developers with a large collective pool of resources, could undertake. Devices in the "consumer products" and "Star Wars" categories were considered to have a low enough risk for a single developer to take on.

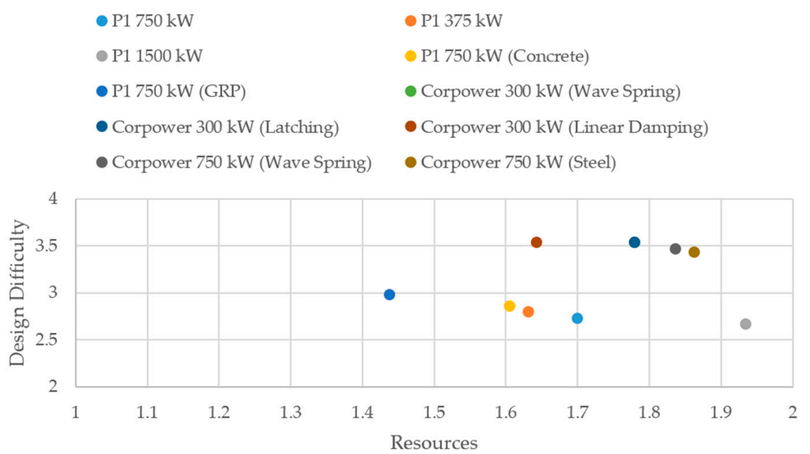

Figure 3. Design difficulty risk plotted against resources risk, indicating how different development approaches introduce risk in different ways.

With an understanding of the LCOE and development risks of each device, the relationship between the LCOE and risk was used to determine a general trend in the data, and this can be seen in Figure 4. The P10, average and P90 trend lines are shown on this plot. They show a general trend that in order to obtain the lowest cost of electricity, a developer must have a higher appetite for risk in order to reach these cost levels. Table 30 shows the equations and R^2 values for these trend lines. The R^2 values for all three trend lines are between 0.5 and 0.6, showing that the trend lines do not fit the data well; however, they are suitable for showing the general trend in the data. This plot can also be used to identify projects that have a similar risk but a significantly different LCOE, enabling promising developments to be easily identified and unattractive ones to be discarded. This leads to the introduction of the RR ratio which is a numerical way of comparing the LCOE and the risk of different developments.

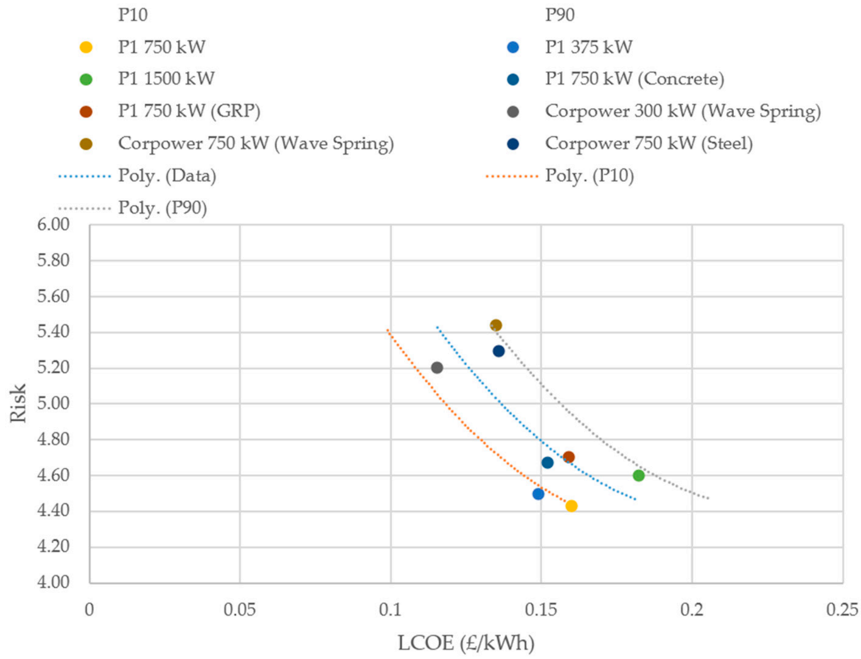

Figure 4. Accessibility vs. availability for mature and early devices in Ireland and Greece [25].

Table 30. Comparison of LCOE results to validate the presented LCOE model.

Trend Line	Equation	R^2
Average	$y = 122.85x^2 - 50.994x + 9.6763$	0.565
P10	$y = 130.04x^2 - 49.547x + 9.0408$	0.537
P90	$y = 114.78x^2 - 52.296x + 10.372$	0.599

3.5. RR Ratio

A comparison of the RR ratios for each different device can be seen in Figure 5. As mentioned in Section 3.5, the RR ratio can be thought of as the efficiency of the allocation of risk. A lower RR ratio indicates a more efficient allocation of risk. By comparing RR ratios of the design changes detailed in the case study, we can determine how risk-efficient each is, and identify which technologies a developer should prioritise investing in. The plot shows that the highest RR ratio is attributed to the CorPower Ocean device acting under latching control, indicating that this development has not spent risk efficiently, and the lowest RR ratio is given by the 300 kW CorPower Ocean device acting under the WaveSpring control, indicating the most "risk-efficient" device.

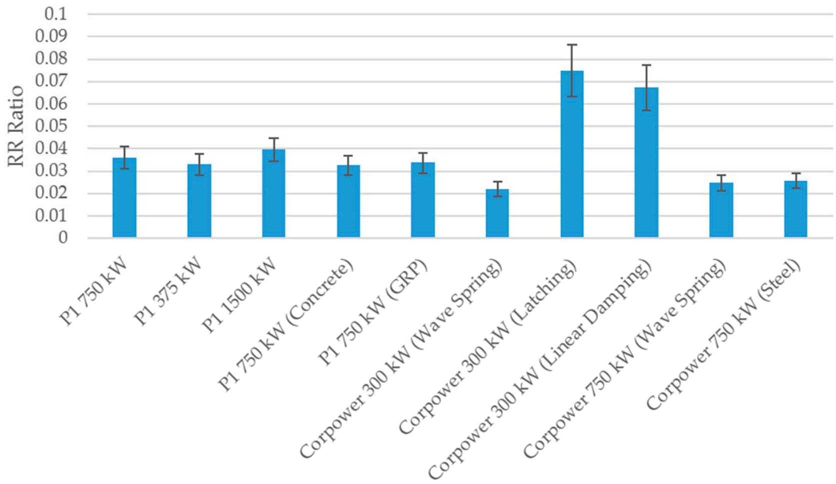

Figure 5. RR ratio of devices in the case studies at the Ireland location.

3.6. Optimal Development Path for Wave Energy

By comparing the RR ratios of different design changes to the reference case for each case study, we are able to establish the percentage improvement in RR ratio, and therefore compare the risk efficiency of different design changes, in order to categorise the optimal development path that WECs should take. Table 31 shows the percentage reduction in the RR ratio of different design changes compared to the reference case for each case study. The results show that the latching and linear damping CorPower Ocean devices are a very inefficient allocation of risk with an increase in the RR ratio of 238% and 236%, respectively. By ranking the RR ratios of each device from the highest reduction in the RR ratio, we can determine the optimal development path for WECs.

By comparing the change in the RR ratio of different design changes with respect to a single reference case, we can determine how efficiently project risk is allocated to it compared to alternative design decisions. This is a tool which could be used by developers when planning their development strategy to ensure that their organisational resources are allocated as efficiently as possible. As an example, the devices featured in each of the case studies have been compared against the reference Pelamis P1 750 kW to show how risk-efficient other design decisions are.

The results show that the most efficient use of risk is the 300 kW CorPower Ocean device, which gave a most likely reduction in the RR ratio of 39%. This suggests that, for the particular locations used in this study, and for the alternative design options available, the most efficient way to spend risk is by developing a smaller device that is well tuned to the sea conditions in which it is deployed, in terms of physical scale, and the control system under which it acts.

Table 31. TRLs and uncertainty ranges used in the LCOE analysis.

Rank	Device	Sub-System	% Reduction in RR Ratio
1	300 kW CorPower Ocean (WaveSpring)	Control	39%
2	750 kW CorPower Ocean (GRP)	Combined	31%
3	750 kW CorPower Ocean (Steel)	PTO	29%
4	750 kW Pelamis P1 (Concrete)	Structure	10%
5	375 kW Pelamis P1 (Steel)	Scale	8%
6	750 kW Pelamis P1 (GRP)	Material	6%

4. Conclusions

The paper has presented a new methodology for assessing investment in marine energy technologies. By considering both the LOCE and development risks, the feasibility of different development approaches can be compared in order to identify the optimal development path for the industry.

By applying this methodology to a number of different case studies it was possible to characterise the LCOE and development risk and therefore the value for risk for a number of design changes, in order to rank them. It was shown how the feasibility of a WEC development could be determined by the relationship between its design difficulty and resource risk on a risk plot.

The concept of an RR ratio was introduced to enable this. This allowed the risk and LCOE of a WEC to be compared, in order to evaluate the value for risk on each different design change. The RR ratio for each was calculated, and by comparing the reduction in the RR ratio of each to a reference case, the improvement in the utilisation of risk was quantified.

The most efficient utilisation of risk was found to be through developing a device that is well tuned to the sea state in which it operates in terms of its scale and control regime, and that exhibits an efficient power take-off system with significant potential for cost reduction, as was shown by the 300 kW CorPower device.

The study showed that changing the structural material would lead to a slight reduction in cost for the risk "spent"; however, it was recognised that design changes that improve the device's energy capture should drive development as these were found to be more risk-efficient than implementing cost reductions introduced through the implementation of new materials.

In general, it was found that to develop cost-effective devices, a developer was exposed to substantial levels of development risk. A general trend was observed that a low cost of electricity can only be obtained through increased allocation of project risk, suggesting that in order to unlock the cost reductions required to be competitive with offshore wind, high development risks will have to be split between developers.

This model should be used as a framework to categorise the LCOE and risk of many different WEC technologies, to allow the suitability of each to be assessed, aiding the formulation of a development path for wave energy converters to ultimately accelerate the convergence of a dominant design. For example, each PTO system in the PTO call guidance programme could be categorised for LCOE and risk in the way detailed in this thesis, to aid in the identification of the most promising technologies. If similar schemes to the PTO call guidance scheme by Wave Energy Scotland were established to accelerate development of other features of marine energy devices, such as control strategies, structural configuration, and even categories out of the scope of this thesis, such as mooring design, then this method could be used to categorise each different design. This would allow the cost reduction potential and risk of various combinations of the technologies to be determined and used to identify the most feasible development path for wave energy. The concepts discussed in this paper are equally applicable to tidal energy and perhaps even industries outside of marine energy.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. LCOE Calculation Data

Appendix A.1. Sea States

Appendix A.1.1. Ireland (Belmullet Test Site) Sea State Matrix

Ireland Sea States		T (s)																			
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Hs (m)	**0.5**														2						
	1					54		136	26			2			2	2					
	1.5					155		440	197	82		22									
	2					32		559	453	253		96	28		4						
	2.5							274	636	352		209	57		9						1
	3							42	399	380		176	77		13						
	3.5							1	196	441		215	78		16	7					
	4								37	338		249	83		22	5	5		1		
	4.5								4	143		229	119		25	5	4		1		
	5									58		206	113		18	3	8		3		
	5.5									5		149	116		31	4			1		
	6											57	120		37	3					1
	6.5											17	69		35	1	5				
	7											6	29		42	9	4		1		
	7.5												16		36	15	2				
	8												6		31	15	4				
	8.5												1		15	9	7				
	9														4	14	4				
	9.5														6	13	1		1		
	10														2	9	1				
	10.5															2					
	11																1				
	11.5																				
	12																				

Figure A1. Ireland sea state matrix.

Appendix A.1.2. Greece (Ionian Sea) Sea State Matrix

Greece Sea States		T (s)																			
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Hs (m)	**0.5**		18	368	894	201	9	9													
	1			263	1761	1445	307	131	18												
	1.5				140	622	289	534	44												
	2					193	105	359	123												
	2.5					44	70	184	158	9											
	3						18	88	96	18											
	3.5							44	61	18											
	4							18	35	18											
	4.5								18	9											
	5								9												
	5.5																				
	6																				
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	7																				
	7.5																				
	8																				
	8.5																				
	9																				
	9.5																				
	10																				
	10.5																				
	11																				
	11.5																				
	12																				

Figure A2. Greece sea state matrix.

Appendix A.2. Power Matrices

Appendix A.2.1. Pelamis P1 750 kW Power Matrix (kW)

Pelamis P1 750 kW		T(s)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
H(m)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	7.5	19.5	36.75	48.75	53.25	50.25	44.25	37.5	31.5	26.25	21.75	12.75	0	0	0	0
	1.5	0	0	0	0	18	46.5	84.75	114	123.75	117	102.75	87	72.75	60.75	51	40.5	31.5	26.25	21.75	15.75
	2	0	0	0	0	42.75	84	150	186.75	197.25	188.25	174	153.75	128.25	108	90	75	63	52.5	43.5	33
	2.5	0	0	0	3.75	66.75	131.25	219	279	298.5	285	257.25	222	192	167.25	139.5	117	97.5	81.75	68.25	53.25
	3	0	0	0	42.75	121.5	193.5	306	372	385.5	362.25	326.25	296.25	264.75	226.5	193.5	167.25	140.25	117.75	97.5	78
	3.5	0	0	0	74.25	172.5	260.25	394.5	475.5	487.5	450.75	400.5	368.25	330.75	285	252	218.25	184.5	159.75	133.5	111.75
	4	0	0	33.75	118.5	229.5	327.75	486	574.5	579.75	549	485.25	431.25	382.5	339	313.5	272.25	231	201	168.75	142.5
	4.5	0	0	89.25	201.75	315	396.75	592.5	656.25	636.75	610.5	561.75	501.75	439.5	388.5	362.25	330.75	281.25	243	202.5	167.25
	5	0	0	113.25	239.25	365.25	460.5	666	743.25	742.5	691.5	410.25	586.5	516.75	452.25	399.75	367.5	325.5	293.25	252.75	219.75
	5.5	0	0	247.5	365.25	461.25	532.5	693	750	750	750	699	648.75	595.5	520.5	457.5	404.25	377.25	331.5	304.5	278.25
	6	0	0	381.75	489	555.75	604.5	711.75	750	750	750	750	692.25	639	595.5	516	455.25	402.75	383.25	337.5	315
	6.5	0	0	518.25	617.25	651.75	676.5	730.5	750	750	750	750	724.5	683.25	622.5	588	505.5	449.25	393	371.25	322.5
	7	0	0	645	737.25	740.25	742.5	747.75	750	750	750	750	750	732	661.5	600.75	572.25	491.25	444	414	376.5
	7.5	0	0	659.25	750	750	750	750	750	750	750	750	750	747.75	714	634.5	567	532.5	485.25	454.5	415.5
	8	0	0	659.25	750	750	750	750	750	750	750	750	750	750	742.5	680.25	597	574.5	524.25	494.25	453.75
	8.5	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	699	628.5	615.75	563.25	534.75	492.75
	9	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	707.25	655.5	657	602.25	574.5	531.75
	9.5	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	714	682.5	699	642	615	569.25
	10	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	721.5	703.5	728.25	681	657.75	619.5
	10.5	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	729	716.25	741.75	720	703.5	684.75
	11	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	738.75	731.25	750	747.75	740.25	736.5
	11.5	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750
	12	0	0	659.25	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750

Figure A3. Pelamis P1 Power Matrix (750 kW).

Appendix A.2.2. Pelamis P1 375 kW Power Matrix (kW)

Pelamis P1 375 kW		T(s)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
H(m)	0.5	0	0	0	1	4	9	14	16	15	13	11	9	8	5	2	0	0	0	0	0
	1	0	0	0	3	11	24	36	41	40	35	29	24	19	15	9	6	5	4	3	2
	1.5	0	0	0	7	27	53	76	85	82	74	64	52	43	35	29	23	19	14	11	7
	2	0	0	1	14	48	89	126	141	137	123	105	89	75	62	51	42	34	26	20	13
	2.5	0	0	7	40	82	136	182	196	186	166	149	131	110	93	78	65	53	42	32	22
	3	0	1	17	65	119	185	242	257	242	213	191	168	146	127	107	91	76	62	47	32
	3.5	0	7	47	105	161	238	299	306	292	262	230	201	178	162	139	117	98	80	61	41
	4	0	11	73	141	200	286	351	359	337	226	278	241	210	188	167	146	125	105	81	55
	4.5	0	25	140	201	248	316	367	375	375	344	320	287	248	216	194	173	155	140	108	73
	5	0	42	220	269	298	339	370	375	375	374	345	318	288	250	217	197	177	160	123	84
	5.5	0	59	300	338	348	362	373	375	375	375	365	344	311	283	248	216	197	175	134	91
	6	0	68	341	373	373	374	375	375	375	375	374	365	334	299	270	243	223	203	156	106
	6.5	0	69	344	375	375	375	375	375	375	375	375	373	358	318	289	267	248	226	175	119
	7	0	69	344	375	375	375	375	375	375	375	375	375	366	334	312	292	272	250	193	131
	7.5	0	69	344	375	375	375	375	375	375	375	375	375	368	344	333	316	296	274	211	144
	8	0	69	344	375	375	375	375	375	375	375	375	375	369	353	352	340	321	300	232	158
	8.5	0	69	344	375	375	375	375	375	375	375	375	375	371	360	363	359	348	335	260	177
	9	0	69	344	375	375	375	375	375	375	375	375	375	373	367	371	374	370	367	286	195
	9.5	0	69	344	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	292	199
	10	0	71	351	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	292	199
	10.5	0	78	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	292	199
	11	0	78	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	292	199
	11.5	0	78	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	292	199
	12	0	78	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	375	292	199

Figure A4. Pelamis P1 power matrix (scaled to 375 kW).

Appendix A.2.3. Pelamis P1 1500 kW Power Matrix (kW)

Pelamis P1 1500 kW		T(s)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
H(m)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	4	14	28	43	54	58	55	49	42	36	31	26	21	14	0	0
	1.5	0	0	0	0	12	37	74	115	144	154	146	130	113	97	82	70	58	44	21	17
	2	0	0	0	0	24	72	136	208	257	274	260	235	206	176	150	128	109	94	72	61
	2.5	0	0	0	0	47	125	219	327	388	406	388	362	325	281	240	205	176	155	126	106
	3	0	0	0	5	74	190	322	467	564	597	570	522	460	403	355	307	265	234	188	160
	3.5	0	0	0	11	86	204	340	489	586	619	589	539	478	421	371	321	278	246	199	169
	4	0	0	0	61	185	328	492	680	788	811	759	692	634	576	509	443	393	354	288	247
	4.5	0	0	6	103	265	437	631	852	979	998	926	836	768	699	621	552	498	450	370	324
	5	0	0	53	182	365	554	773	1028	1160	1167	1106	997	896	804	721	659	608	552	456	400
	5.5	0	0	128	319	524	702	928	1217	1308	1275	1222	1135	1031	920	820	752	706	662	547	477
	6	0	0	162	383	612	813	1061	1370	1486	1485	1383	894	1093	1078	958	853	780	735	638	577
	6.5	0	0	198	431	652	845	1082	1378	1489	1488	1404	989	1135	1105	985	876	799	749	656	592
	7	0	0	363	652	841	991	1179	1415	1500	1500	1500	1415	1324	1229	1108	984	887	813	738	661
	7.5	0	0	560	914	1063	1165	1289	1444	1500	1500	1500	1500	1414	1317	1231	1119	1003	917	802	758
	8	0	0	748	1166	1276	1329	1392	1471	1500	1500	1500	1500	1462	1395	1297	1212	1127	1014	877	784
	8.5	0	0	925	1405	1478	1482	1489	1497	1500	1500	1500	1500	1500	1476	1381	1263	1184	1145	963	881
	9	0	0	928	1409	1481	1485	1490	1497	1500	1500	1500	1500	1500	1479	1392	1276	1191	1143	975	893
	9.5	0	0	946	1432	1500	1500	1500	1500	1500	1500	1500	1500	1500	1497	1460	1358	1237	1141	1054	972
	10	0	0	946	1432	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1491	1424	1311	1196	1130	1044
	10.5	0	0	946	1432	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1450	1356	1259	1212	1123
	11	0	0	946	1432	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1458	1383	1311	1291	1198
	11.5	0	0	946	1432	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1459	1386	1318	1302	1208
	12	0	0	946	1432	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1465	1411	1369	1380	1286

Figure A5. Pelamis P1 power matrix (scaled to 1500 kW).

Appendix B. Justification of Risk Scores

Appendix B.1. Design Difficulty

Appendix B.1.1. How Scalable Is the Sub-System?

Table B1. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW P1 375 kW P1 1500 kW Corpower 750 kW (Steel)	1	Device is made from steel plate which is formed and welded together. Steel plate can be considered to be infinitely scalable—large ships are made this way, these are larger than any WEC is likely to be.
P1 750 kW (Concrete)	1	The concrete Pelamis was considered to be infinitely scalable—widespread use of concrete in the construction industry to make massive structures.
P1 750 kW (GRP) Corpower 300 kW (Wave Spring) Corpower 300 kW (Latching) Corpower 300 kW (Linear Damping) Corpower 750 kW (Wave Spring)	2	GRP was considered to be scalable up to a point. It has been extensively proven on small to moderate sized projects, however literature revealed that regulations within the shipping industry preventing the use of composites in large ships due to the high fire risk they pose [32]. This could be an issue developing a very large WEC.

Table B2. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW P1 375 kW P1 1500 kW P1 750 kW (Concrete) P1 750 kW (GRP)	2	Pelamis P1 uses conventional off the shelf hydraulics. These components are available in a range of sizes up to a point, however from the author's knowledge of the hydraulics industry, at very large scales standard components may not exist, and it is likely that bespoke components would need to be manufactured. e.g., specially made rams or hydraulic motors for a very large Pelamis device.
Corpower 300 kW (Wave Spring) Corpower 300 kW (Latching) Corpower 300 kW (Linear Damping) Corpower 750 kW (Wave Spring and Steel)	2	The Corpower PTO was considered to be scalable up to a point, however it was assumed that at very large sizes the design details may need changed. Not enough data exists to accurately assess this.

Table B3. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW P1 375 kW P1 1500 kW P1 750 kW (Concrete) P1 750 kW (GRP) Corpower 300 kW (Wave Spring) Corpower 300 kW (Latching) Corpower 300 kW (Linear Damping) Corpower 750 kW (Wave Spring and Steel)	2	The control system is thought to be well suited up to a certain size, however the device will get to a point where its dynamics fall out of sync with the ocean waves in the way in which it was designed.

Appendix B.1.2. How Well Suited Is the Technology to Dealing with the Loading Placed upon It?

Table B4. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW P1 375 kW P1 1500 kW Corpower 750 kW (Steel)	2	A structural design review of the Pelamis P1 indicated how the steel device would perform under fatigue (scores 3), extreme loading (scores 1) and ship impact (scores 2). This gave a total survivability score of 6, translating into a score of 2 for the survivability metric.
P1 750 kW (Concrete)	2	A structural design review of the concrete Pelamis P1 indicated how the device would perform under fatigue (scores 1), extreme loading (scores 1) and ship impact (scores 2). This gave a total survivability score of 6, translating into a score of 2 for the survivability metric.
P1 750 kW (GRP) Corpower 300 kW (Wave Spring) Corpower 300 kW (Latching) Corpower 300 kW (Linear Damping) Corpower 750 kW (Wave Spring)	2	The same survivability logic was applied to the Corpower GRP devices as the GRP Pelamis, which therefore scored the same.

Table B5. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW P1 375 kW P1 1500 kW P1 750 kW (Concrete) P1 750 kW (GRP)	2	Industrial hydraulics can be designed to withstand very large loads and systems can be designed with blow off valves to protect the circuit (scores a 1 for extreme loading). Common to have cyclic loading on hydraulic systems however no standout fatigue performance in systems was recognised (scored 2). Ship impact was thought to be very destructive to hoses and other hydraulic components (scores 3).
Corpower 300 kW (Wave Spring) Corpower 300 kW (Latching) Corpower 300 kW (Linear Damping) Corpower 750 kW (Wave Spring and Steel)	3	All loads assumed to go through gearbox, without a load decoupling mechanism, suggesting little protection against extreme loading at PTO level (scores 3). No standout features identified with respect to fatigue (scores a 2). PTO unlikely to be serviceable after a ship impact, main concern would be input shaft bending (scores a 3).

Table B6. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	2	The control system for both concepts is designed to detune the device to sit under the surface of the waves in a storm, no stand out features so control survivability was considered as average [19,23].
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.3. How Efficiently Does the Technology Perform Its Prime Function?

Table B7. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	2	From the Pelamis P1 structural analysis document; the rigidity of steel was determined to be average (scores 2), resistance to buckling was determined to be poor (scores 3) and ballast requirement was determined to be average (scores 2) [19].
P1 375 kW		
P1 1500 kW		
Corpower 750 kW (Steel)		
P1 750 kW (Concrete)	1	From the Pelamis P1 structural analysis document; the rigidity of concrete was determined to be average (scores 2), resistance to buckling was determined to be very good (scores 1) and ballast requirement was determined to be low (scores 1) [19].
P1 750 kW (GRP)	3	From the Pelamis P1 structural analysis document; the rigidity of GRP was determined to be poor (scores 3), resistance to buckling was determined to be poor (scores 3) and ballast requirement was determined to be high (scores 3). This logic was continued for the GRP Corpower device [19].
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)		

Table B8. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW	2	Documentation on the PTO of the Pelamis P1 revealed that the efficiency of the system was around 80% translating to an efficiency score of 2. [15]
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	1	The efficiency of the Corpower WEC is commercially sensitive and cannot be disclosed, however translates to a risk score of 1. [23]
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B9. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	1	Theoretical capture width of a line absorber of two wave lengths in length is 0.73λ, compares well to other WEC principals, indicating the potential of the control regime [33].
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	3	Theoretical maximum capture width of a heaving body is 0.16λ, indicating a low theoretical capture width compared to other WEC types [15].
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.4. How Well Suited Is the Technology for the Marine Environment?

Table B10. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	2	Steel outer structure of Pelamis P1 will rust if not treated therefore. Needs painted for protection.
P1 375 kW		
P1 1500 kW		
Corpower 750 kW (Steel)		
P1 750 kW (Concrete)	1	Concrete is well suited to the marine environment. No treatment is required.
P1 750 kW (GRP)	1	GRP is well suited to the marine environment and would not need any additional coatings or protection after the forming process has been completed [19]. Applies to both Pelamis and Corpower devices.
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)		

Table B11. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW	3	Off the shelf hydraulics are typically not water sealed or designed to work while submerged in water therefore these components would need packaged in a watertight space. Power electronics also need to be kept dry.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	3	Steel gearbox would rust if exposed to sea water. Bearings are unlikely to be water sealed. Electric generators also unlikely to be sealed, therefore PTO needs sealed in a watertight container.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B12. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	1	This metric does not affect the control system. Scores lowest risk.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.5. How Well Understood Is the Technology Exhibited in the Sub System?

Table B13. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	1	Design and construction of floating steel structures extensively understood.
P1 375 kW		
P1 1500 kW		
Corpower 750 kW (Steel)		
P1 750 kW (Concrete)	1	Concrete is widely used and knowledge is very good.
P1 750 kW (GRP)	2	GRP is understood however knowledge is less wide spread than steel and concrete and experts are required to implement effectively.
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)		

Table B14. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW	1	Hydraulic systems are widely understood by many hence the knowledge required to implement these systems is widely available.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	1	The gears, generators, flywheels and dampers that make up the Corpower PTO are very common and well understood technologies, hence the knowledge complexity risk is low.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B15. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	3	Developing this control system requires in very depth knowledge of dynamics and wave mechanics. Knowledge complexity was considered to be the highest risk. This was considered to apply to the control system for both the Pelamis P1 and the Corpower WEC.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.6. How Well Established Is the Reliability of the Technology?

Table B16. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	1	As steel floating structures are very well understood, the reliability of such structures is well known and tested.
P1 375 kW		
P1 1500 kW		
Corpower 750 kW (Steel)		
P1 750 kW (Concrete)	3	No one has made a floating concrete WEC before, additionally fatigue is hard to calculate for reinforced concrete. Reliability is unknown.
P1 750 kW (GRP)	2	Reliability of GRP as a structural material is understood and has been researched and tested in different industries. Data for its use on large WECs is however limited.
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B17. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW	1	Reliability of off the shelf components is very well understood—components are extensively tested in development and tried and tested in other industries.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	3	As the Corpower PTO is a bespoke device, and a full sized system has not been tested in the marine environment, the PTO reliability was determined to be unknown.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B18. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	2	Reliability of control system in real waves relatively unknown, there is however some test data present from the few deployments of the device.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	3	Reliability of control system in real waves unknown as a full size device has never been tested in the ocean environment.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.7. What Levels of Maintenance Does the Technology Require?

Table B19. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	3	Literature revealed that the Pelamis is expected to need touch up paint at one point though out its life.
P1 375 kW		
P1 1500 kW		
Corpower 750 kW (Steel)		
Corpower 750 kW (Steel)		
P1 750 kW (Concrete)	1	Concrete was found to be maintenance free [19].
P1 750 kW (GRP)	1	GRP was found to be maintenance free [19].
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)		

Table B20. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW	3	Literature revealed that the P1 PTO needs replacement at one point in its lifetime.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	3	Literature suggests that the drive units will need replacement at some point in the lifetime of the device.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B21. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	1	The control systems for both devices is expected to need very little, if any, maintenance.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.8. How Many Manufacturing Steps Are Required to Take the Subsystem from the Final Engineering Design to a Fully Operational Device?

Table B22. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	3	Structure of the Pelamis P1 is novel and bespoke, parts need to be cut, formed and joined. Considered as 3 steps.
P1 375 kW		
P1 1500 kW		
Corpower 750 kW (Steel)		
P1 750 kW (Concrete)	4	Concrete structure needs mould to be made, concrete to be poured with wires tensioned, mould removal and final assembly. This was considered as 4 or more steps.
P1 750 kW (GRP)	4	Manufacturing a GRP structure requires many steps—moulds must be made, the layup must be applied to the mould, the mould closed, resin injected into the mould, then the curing process. Determined to be made of a minimum of 4 steps.
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)		

Table B23. PTO: risk scores and justifications.

PTO	Score	Justification
P1 750 kW	2	The off the shelf components require assembly into a system and are then integrated into the device. Two step process.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	3	PTO for the Corpower device is bespoke, most of the main components will need to be manufactured and assembled. The cascade gearbox is bespoke and requires advanced machining work, before assembly and integration into the device. Determined to be 3 steps.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Table B24. Control: risk scores and justifications.

Control	Score	Justification
P1 750 kW	4	Many testing steps required to produce working control system. Evidence of many different tank tests at different scales for both devices. Determined to be 4 or more steps.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)		
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.1.9. How Manufacturable Is the Technology Used within the Sub-System?

Table B25. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW and Corpower 750 kW (Steel)	2	The 750 kW Pelamis determined to be manufactured in moderate production numbers. The complexity of the manufacturing process was thought to be minimal due to the relative ease of shaping and joining steel plate.
P1 375 kW	3	High production numbers and same process complexity logic as 750 kW device.
P1 1500 kW	1	Low production numbers and same process complexity logic as 750 kW device.
P1 750 kW (Concrete)	3	Pouring concrete into a mould and pre-tensioning the reinforcement steel was considered a complex manufacturing process. 750 kW device made in moderate volumes.
Corpower 300 kW (Wave Spring)	4	Manufacturing GRP was determined to be a complex manufacturing process. Being below 500 kW these devices were considered to be made in large production volumes.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)	3	Manufacturing GRP was determined to be a complex manufacturing process. Devices rated between 0.5 and 1 MW, production volumes considered to be moderate.
P1 750 kW (GRP)		

Table B26. PTO: risk scores and justifications.

<table>
<tr><th>PTO</th><th>Score</th><th>Justification</th></tr>
<tr><td>P1 750 kW</td><td rowspan="4">2</td><td>Hydraulic PTO only requires components to be assembled together—straightforward process. Moderate production numbers.</td></tr>
<tr><td>P1 375 kW (GRP)</td><td>Hydraulic PTO only requires components to be assembled together—straightforward process. Large production numbers.</td></tr>
<tr><td>P1 750 kW (Concrete)</td><td rowspan="2">Hydraulic PTO only requires components to be assembled together—straightforward process. Moderate production numbers.</td></tr>
<tr><td>P1 750 kW (GRP)</td></tr>
<tr><td>P1 1500 kW</td><td>1</td><td>Hydraulic PTO only requires components to be assembled together—straightforward process. Small production numbers.</td></tr>
<tr><td>Corpower 300 kW (Wave Spring)</td><td rowspan="3">4</td><td rowspan="3">Components in cascade gearbox would require advanced but widely available technology to manufacture. Other components are assumed to be bought as standard parts and simply assembled together. Large production volumes.</td></tr>
<tr><td>Corpower 300 kW (Latching)</td></tr>
<tr><td>Corpower 300 kW (Linear Damping)</td></tr>
<tr><td>Corpower 750 kW (Wave Spring and Steel)</td><td>3</td><td>Same as other Corpower PTOs however produced in moderate production volumes.</td></tr>
</table>

Table B27. Control: risk scores and justifications.

<table>
<tr><th>Control</th><th>Score</th><th>Justification</th></tr>
<tr><td>P1 750 kW</td><td rowspan="9">2</td><td rowspan="9">Requires specialist computer modelling tools and wave tank test equipment to develop. Wave simulation software and wave tanks are assumed to be advanced, but well established technologies. Independent of production volumes.</td></tr>
<tr><td>P1 375 kW</td></tr>
<tr><td>P1 1500 kW</td></tr>
<tr><td>P1 750 kW (Concrete)</td></tr>
<tr><td>P1 750 kW (GRP)</td></tr>
<tr><td>Corpower 300 kW (Wave Spring)</td></tr>
<tr><td>Corpower 300 kW (Latching)</td></tr>
<tr><td>Corpower 300 kW (Linear Damping)</td></tr>
<tr><td>Corpower 750 kW (Wave Spring and Steel)</td></tr>
</table>

Appendix B.2. Resources

Appendix B.2.1. What Is the Total Cost of a Pilot Device?

Table B28. Structure: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	3, 3, 4	P10—£13,383,695. Average—£14,919,338. P90—£16,547,591. Scores 3, 3, 4. (P10, average, P90)
P1 375 kW	3, 3, 3	P10—£10,772,590. Average—£11,753,375. P90—£12,865,759. Scores 3, 3, 3. (P10, average, P90)
P1 1500 kW	4, 4, 5	P10—£16,371,734. Average—£18,241,800. P90—£20,380,437. Scores 4, 4, 5. (P10, average, P90)
P1 750 kW (Concrete)	3, 3, 4	P10—£13,570,693. Average—£14,977,575. P90—£16,559,417. Scores 3, 3, 4. (P10, average, P90)
P1 750 kW (GRP)	3, 4, 4	P10—£13,570,724. Average—£15,073,104. P90—£16,679,225. Scores 3, 4, 4. (P10, average, P90)
Corpower 300 kW (Wave Spring)	2, 2, 3	P10—£9,387,824. Average—£10,179,709. P90—£11,086,531. Scores 2, 2, 3. (P10, average, P90)

Table B28. *Cont.*

Structure	Score	Justification
Corpower 300 kW (Latching)	3, 3, 4	P10—£13,300,704. Average—£14,789,700. P90—£16,467,015. Scores 3, 3, 4. (P10, average, P90)
Corpower 300 kW (Linear Damping)	2, 3, 3	P10—£9,714,931. Average—£10,516,052. P90—£11,418,993. Scores 2, 3, 3. (P10, average, P90)
Corpower 750 kW (Wave Spring)	3, 3, 3	P10—£10,288,754. Average—£11,277,621. P90—£12,365,014. Scores 3, 3, 3. (P10, average, P90)

Appendix B.2.2. What Learning Investment Is Required to Develop the Technology?

Table B29. Whole device: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	3, 6, 9	P10—£2.95 billion. Average—£5.27 billion. P90—£8.74 billion. Scores 3, 6, 9. (P10, average, P90)
P1 375 kW	5, 6, 9	P10—£4.08 billion. Average—£5.78 billion. P90—£8.45 billion. Scores 5, 6, 9. (P10, average, P90)
P1 1500 kW	2, 5, 10	P10—£1.93 billion. Average—£4.84 billion. P90—£9.27 billion. Scores 2, 5, 10. (P10, average, P90)
P1 750 kW (Concrete)	3, 6, 9	P10—£2.97 billion. Average—£5.36 billion. P90—£8.86 billion. Scores 3, 6, 9. (P10, average, P90)
P1 750 kW (GRP)	3, 6, 9	P10—£3.06 billion. Average—£5.40 billion. P90—£8.82 billion. Scores 3, 6, 9. (P10, average, P90)
Corpower 300 kW (Wave Spring)	4, 6, 8	P10—£3.56 billion. Average—£5.08 billion. P90—£7.3 billion. Scores 4, 6, 8. (P10, average, P90)
Corpower 300 kW (Latching)	6, 8, 11	P10—£5 billion. Average—£7.34 billion. P90—£10.34 billion. Scores 6, 8, 11. (P10, average, P90)
Corpower 300 kW (Linear Damping)	4, 5, 8	P10—£3.62 billion. Average—£5.22 billion. P90—£7.46 billion. Scores 4, 5, 8. (P10, average, P90)
Corpower 750 kW (Wave Spring)	4, 6, 9	P10—£3.9 billion. Average—£5.62 billion. P90—£8.2 billion. Scores 4, 6, 9. (P10, average, P90)

Appendix B.2.3. How Long Does the Device Take to Manufacture?

Table B30. Whole device: risk scores and justifications.

<table>
<tr><th>Structure</th><th>Score</th><th>Justification</th></tr>
<tr><td>P1 750 kW</td><td rowspan="4">3</td><td rowspan="4">Literature revealed that at full capacity PWP would produce 10 MW per year. Based on a 40 h working week it was calculated that 2080 h a year would be available to manufacture ten 1 MW devices, hence the manufacturing output is 208 h/MW. It has been recognised that this is a fairly crude justification and more research is required to accurately obtain a score.</td></tr>
<tr><td>Corpower 750 kW (Steel)</td></tr>
<tr><td>P1 375 kW</td></tr>
<tr><td>P1 1500 kW</td></tr>
<tr><td>P1 750 kW (Concrete)</td><td>3</td><td>Literature revealed that concrete can take several weeks to set properly, therefore, it was determined that the device would take significantly longer to manufacture than an offshore wind turbine. This assumption has however been made in ignorance due to no reliable data available for this particular metric.</td></tr>
</table>

Table B30. *Cont.*

Structure	Score	Justification
Corpower 300 kW (Wave Spring)	2	It was assumed that the GRP devices would take a similar time to manufacture (per MW) as offshore wind turbines. Offshore wind turbines are made from a combination of structural steel, GRP and pre-assembled modular units such as the generator, gearbox and power electronics. This was assumed to be similar to the subsystems that make up the GRP structured WECs therefore the manufacturing time was considered to be comparable.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring)		
P1 750 kW (GRP)		

Appendix B.2.4. How Long Does the Device Take to Install in Its Deployment Location?

Table B31. Whole device: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	1	Literature revealed that the Pelamis P1 could be installed in 30 min, well within the minimum 6-h weather window therefore the installation time was thought to be low risk [19]. The 1500 kW device was assumed to be installable in under 6 h, as doubling the capacity was thought to only increase installation time a little, if any.
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	1	Literature revealed that the Corpower wave energy converter can be installed and removed within 30 min, well within the minimum 6-h weather window therefore the installation time was thought to be low risk [23]. The 750 kW device was assumed to be installable in under 6 h, as doubling the capacity was thought to only increase installation time a little, if any. Scores 1.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.2.5. What Are the Infrastructure Requirements to Manufacture/Assemble the Device?

Table B32. Whole device: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	1	Devices are all transportable by road so can be manufactured in land. The Pelamis structural design report detailed that there were many locations where concrete and steel P1 structural tubes could be manufactured [19].
P1 375 kW		
P1 750 kW (Concrete)		
P1 1500 kW	2	1500 kW device was deemed too large to transport therefore facilities for manufacture would be required by the sea. It is assumed that this device can be manufactured in existing shipping yards.
P1 750 kW (GRP)	2	The Pelamis structural design report indicated that the choice of manufacturing locations for GRP devices of this scale is limited.
Corpower 300 kW (Wave Spring)	3	This device is too large to be transported by road (see R6) and we know from the Pelamis report that there are limited locations where GRP structures can be built. This suggests that these devices would require a manufacturing facility on the shore. Large GRP structures have been developed by the wind energy industry however this has required serious investments in infrastructure.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

Appendix B.2.6. What Are the Infrastructure Requirements to Transport and Install the Device?

Table B33. Whole device: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	1	The 750 kW Pelamis device is designed to fit onto the back of a lorry in sections for transportation.
P1 375 kW	1	The 375 kW device smaller than 750 kW so should easily fit onto conventional lorries.
P1 1500 kW	3	The 1500 kW device is unlikely to fit onto roads within the legal size and weight restrictions.
P1 750 kW (Concrete)	3	Pelamis P1 structural design report classifies handling Concrete device as "v. difficult" [19]. Unlikely to be transportable by road.
P1 750 kW (GRP)	1	Pelamis P1 structural design report classifies handling GRP device as "easy" [19]. Likely that it can be transported by road.
Corpower 300 kW (Wave Spring)	3	The dimensions of this device suggest that the moulded structures will not be transportable by road. The dimensions cannot be disclosed however they are too large to realistically fit onto a standard HGV.
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)	3	The diameter of this device is expected to be significantly larger than the 300 kW device, which is not transportable by road.

Appendix B.2.7. What Are the Infrastructure Requirements to Servicing the Device?

Table B34. Whole device: risk scores and justifications.

Structure	Score	Justification
P1 750 kW	2	Literature revealed that the Pelamis P1 would require removal from site to conduct all routine maintenance [15].
P1 375 kW		
P1 1500 kW		
P1 750 kW (Concrete)		
P1 750 kW (GRP)		
Corpower 300 kW (Wave Spring)	2	Literature revealed that the Corpower WEC would require removal from site to conduct all routine maintenance [23].
Corpower 300 kW (Latching)		
Corpower 300 kW (Linear Damping)		
Corpower 750 kW (Wave Spring and Steel)		

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